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ORIGINAL PAPER

Biological invasions in World Heritage Sites: current status and a proposed monitoring and reporting framework

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Abstract

UNESCO World Heritage Sites (WHS) are areas of outstanding universal value and conservation importance. They are, however, threatened by a variety of global change drivers, including biological invasions. We assessed the current status of biological invasions and their management in 241 natural and mixed WHS globally by reviewing documents collated by UNESCO and IUCN. We found that reports on the status of biological invasions in WHS were often irregular or inconsistent. Therefore, while some reports were very informative, they were hard to compare because no systematic method of reporting was followed. Our review revealed that almost 300 different invasive alien species (IAS) were considered as a threat to just over half of all WHS. Information on IAS management undertaken in WHS was available for fewer than half of the sites that listed IAS as a threat. There is clearly a need for an improved monitoring and reporting system for biological invasions in WHS and likely the same for other protected areas globally. To address this issue, we developed a new framework to guide monitoring and reporting of IAS in protected areas building on globally accepted standards for IAS assessments, and tested it on seven WHS. The framework requires the collation of information and reporting on pathways, alien species presence, impacts, and management, the estimation of future threats and management needs, assessments of knowledge and gaps, and, using all of this information allows for an overall threat score to be assigned to the protected area. This new framework should help to improve monitoring of IAS in protected areas moving forward.

Keywords Biodiversity · Conservation · Global environmental change · Invasive alien species · IUCN · Management · Protected areas · UNESCO

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Introduction

Key drivers of global change are increasingly threatening the environment and areas with high natural and cultural value (Vitousek et al. 1997; Chape et al. 2005; Brook et al. 2008; Butchart et al. 2010; Watson et al. 2014), making the effective management of over 230,000 protected areas (PAs) globally a critical endeavour (UNEP-WCMC, IUCN and NGS 2019). These PAs safeguard important biodiversity and scenic landscapes and provide ecosystem services, which benefit human well-being and are essential for a sustainable world (Naughton-Treves et al. 2005; Egoh et al. 2007).

Responding to the need for conservation of natural and cultural heritage, the World Heritage Convention was established in the early 1970s by the United Nations Educational, Scientific and Cultural Organisation (UNESCO 1972). As of January 2020, the Convention recognised 1121 [869 cultural, 213 natural, and 39 mixed (cultural-natural)] areas of "Outstanding Universal Value" as World Heritage Sites (WHS). WHS are areas of "cultural and/or natural significance which are so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity" (UNESCO 2017). Natural and mixed WHS account for around 8% of terrestrial and 6% of marine protected surface area worldwide, thus contributing significantly to conservation globally (Strahm, 2008; Bertzky et al. 2014; Osipova et al. 2017). Similar to other PAs, WHS vary greatly in size (from < 20 ha to > 40 million ha; UNEP-WCMC and IUCN 2017); represent many different governance types (Dudley 2008); and differ in the threats they face and their capacities for protection, management and research (Osipova et al. 2017). New WHS are inscribed annually, but the WHS status can also be revoked for two reasons: the WHS has deteriorated to the extent that it has lost those characteristics which determined its inclusion in the World Heritage List; or there was a lack of corrective measures to protect the intrinsic qualities of a WHS from damage by human action (as outlined and within the time proposed by the State Party at the time of inscription). Biological invasions are a major threat to WHS (Osiprova et al. 2017), and can be one of many contributing factors which can lead to sites being put on a danger list (https://www.iucn.org/theme/world-heritage/natural-sites/danger-list). For example, the Galapagos Islands site was added to the danger list in 2007, due to the uncontrolled number of tourists in combination with impacts from biological invasions (https://www.iucn.org/content/galapagos-islands-added-world-heritage-danger-list).

Biological invasions are a key driver of change in the world's PAs, including WHS (Usher 1988; Foxcroft et al. 2013, 2017; Osipova et al. 2017; Padmanaba et al. 2017; Bomanowska et al. 2019; Shackleton et al. 2020). Biological invasions are the process whereby organisms are intentionally or accidentally moved by human activity from their native ranges into new areas, and where some of these 'alien species' establish and spread widely [meaning that they become invasive alien species, (IAS)], leading to negative impacts on native biodiversity, ecosystem services and/or human well-being (Richardson et al. 2000, 2011; IUCN 2000; Jeschke et al. 2014; see Box 1 in Supplementary file 1 for a glossary of terms). IAS impact the values and integrity of PAs by causing the decline and extinction of native species through a variety of mechanisms, such as predation, disease, competition and/or hybridisation (Clavero and García-Berthou 2005; Downey and Richardson 2016), and by altering ecological community structure and landscape/ecosystem function (Angassa 2005; Hejda et al. 2009; Pejchar and Mooney 2009; Vilà et al. 2010; Eldrige et al. 2011). They can also impact human wellbeing and how people experience these PAs (Shackleton et al. 2019). If not managed, the impacts due to existing

IAS are expected to increase over time. Moreover, the number of IAS globally are expected to increase both as more alien species become invasive in the future (e.g. by exiting a lag phase), and as more alien species are introduced (Essl 2011; Bellard et al. 2016; Johnson et al. 2017; Seebens et al. 2017). Thus, the impacts and threat posed by biological invasions continues to grow (Essl et al. 2011; Rouget et al. 2016).

According to the 2017 IUCN World Heritage Outlook assessment, biological invasions are considered the most significant current threat, and the third most significant future threat to WHS globally, particularly in North America and Oceania (Osipova et al. 2017). The overall threat of biological invasions to WHS is well known (Osipova et al. 2014, 2017; Veillon 2014), but detailed global reporting on IAS and their management in WHS is lacking, and only a small number of WHS have in-depth analyses and reports (e.g. Bradshaw et al. 2007; Van Damme and Banfield 2011; Hernandez-Enriquez et al. 2012). Improved knowledge about the presence and effects of IAS, and their current management, is crucial to facilitate decision-making at the site level, and to inform wider policy and management to maintain, or even improve, the outstanding values of WHS. The same can be said for other forms of PAs globally (Shackleton et al. 2020).

This paper provides a detailed assessment of the presence of IAS and their threat to the integrity of natural and mixed WHS, and to assess the implementation of IAS management efforts in WHS. To do this, we reviewed IUCN and UNESCO documents which we found to lack detail in monitoring and reporting. Therefore, we developed and tested a new framework to guide monitoring, assessment, and reporting of IAS in WHS and other protected areas. This proposed monitoring system could help track progress towards the Convention on Biological Diversity (CBD) targets and assist in developing new global standards and best practices for the monitoring and evaluation of biological invasions in all PAs.

Methods

A review of existing monitoring procedures

To ensure the effective conservation of WHS, various impacts and threats are monitored. However, while there are reports detailing the broad-scale impacts of biological invasions and other threats (e.g. Osipova et al. 2014, 2017), in-depth analyses for each of these threats are lacking. To provide more information on the topic, we conducted a detailed review of documents from past UNESCO and IUCN monitoring and reporting activities.

We gathered spatial data from the World Database on Protected Areas (UNEP-WCMC and IUCN 2017), and threat data from the IUCN World Heritage Outlook reports (Osipova et al. 2014, 2017) for all (241) natural and mixed WHS inscribed up to June 2018. UNESCO's World Heritage State of Conservation Information System (https://www.whc.unesco.org/en/soc), and the online portal of the IUCN World Heritage Outlook assessments (https://www.worldheritageoutlook.iucn.org/), store information on the state of WHS, and threats (including biological invasions) to their biodiversity and other values, and can help to track changes in the conditions of these sites through existing monitoring and reporting mechanisms. We reviewed the UNESCO and IUCN websites, and the documents available or cited on those websites, to extract data on the occurrence, impacts/threats and management of biological invasions for each WHS. The reviewed documentation (hereafter referred to as IUCN and UNESCO documents) included website summaries, periodic reports, State of Conservation reports, reactive monitoring mission reports, and World

Heritage Outlook assessments, as well as attached or cited scientific reports and publications. These documents are based on national monitoring mechanisms and processes, as well as internationally driven reporting to UNESCO and the IUCN. WHS are subject to international World Heritage monitoring and reporting processes which currently include: (1) UNESCO's periodic reporting to which States Parties (the countries that are parties to the Convention) contribute on a 6-year regional cycle; (2) reactive monitoring of the 'state of conservation', involving reports and missions, for sites with known issues, undertaken by UNESCO and its technical advisory bodies (IUCN for natural sites) in cooperation with States Parties; and (3) the independent and systematic IUCN World Heritage Outlook assessments for all sites, implemented by IUCN on a 3-year cycle (so far completed in 2014 and 2017; Osipova et al. 2014, 2017). The IUCN and UNESCO monitoring and reporting mechanisms have separate categories for "spreading species", including alien, invasive alien, translocated native, and 'hyper-abundant' native. The majority of the threat data clearly relates to alien (and more specifically invasive alien) species (sensu IUCN 2000; Richardson et al. 2011) and is the focus of this paper (see box 1 in Supplementry file 1). We removed "native invasive species/hyper-abundant native species" from the analysis and only focused on alien species.

These above-mentioned sources were reviewed for each of the 241 WHS, by reading through each dedicated website or document. For each WHS, we extracted data on the listing and reporting of alien species, threats and impacts of IAS, and information on the management of biological invasions. We compiled data on the number of alien species present at each site (either mentioned as a total number and/or each species listed as present in the WHS), noted IAS specifically named in the reports (lists of species), compiled information provided on threats (qualitative descriptions of impacts or citations of other work), and mention of IAS management for the WHS (yes, no or unknown). If management programmes were indicated, we collected further data on control approaches and methods used [preventative measures, eradication attempts, impact reduction or containment attempts, as well as the control techniques being used, including physical, biological, chemical, cultural, utilisation or integrated control (i.e. the use of multiple approaches) and evidence of a strategic plan (yes, no or unknown)].

Development of a monitoring and reporting framework.

The review of these IUCN and UNESCO documents yielded limited information on the presence, threat, and management of IAS within WHS, despite being a part of a comprehensive monitoring strategy. Reporting was irregular and/or incomparable. This is probably because of the lack of a detailed, comprehensive, and standardised monitoring and reporting framework, which is likely to be the case for all categories of PAs globally. We, therefore, developed a framework to improve monitoring and reporting and used seven case studies to test it. This framework combined the approaches of the IUCN World Heritage Outlook for assessing management and threats of IAS to the integrity of WHS (https://www.worldheritageoutlook.iucn.org/); CBD and IUCN for classifying introduction pathways (Hulme et al. (2008) as expanded and adapted by the IUCN (2017); the Environmental Impact Classification of Alien Taxa (EICAT) scheme set out in Blackburn et al. (2014) and Hawkins et al. (2015) (currently being updated by IUCN to be published as an official IUCN standard in 2020); and various other schemes that have developed indicators or guidelines for monitoring biological invasions (e.g. see McGeoch et al. 2010; Latombe et al. 2017; Wilson et al. 2018).

The framework we developed focuses on: monitoring and reporting of the current status of biological invasions in WHS; predicting threats and management needs; and assessing the overall threat level of the site (see Supplementary file 1 for details and instructions on how to apply the framework). The current status relates to evaluating pathways, compiling alien species lists, identifying and reporting key impacts caused by IAS, as well as reporting on the status of management. The section on predictions relates to identifying key threats and management needs that might arise in the future. The last section relates to identifying knowledge gaps and assigning a robust and evidence-based overall rating of the threat level posed by biological invasions to a specific site (for more details, see Supplementary file 1). Test examples using the new framework, and information on how these can be written-up, appear in Supplementary file 2. We suggest that monitoring and reporting should be done by local experts or managers (or regional or international experts knowledgeable about the local situation or area if local capacity is lacking). Future implementation of the monitoring and reporting framework should be driven by state authorities (as part of their reporting duties under the Convention for the sites on their territory) in partnership with local actors to ensure capacity building, learning, and ownership, and should incorporate published literature, grey literature, local research, and local knowledge. However, external processes and experts should help to facilitate this where needed.

The seven in-depth case studies to test the framework were applied to WHS in different social-ecological contexts, and with different reported threat levels from IAS (Fig. 1; Supplementary file 2). This includes sites on five continents, encompassing a range of social and ecological settings, as well as mainland and island WHS. Three sites had

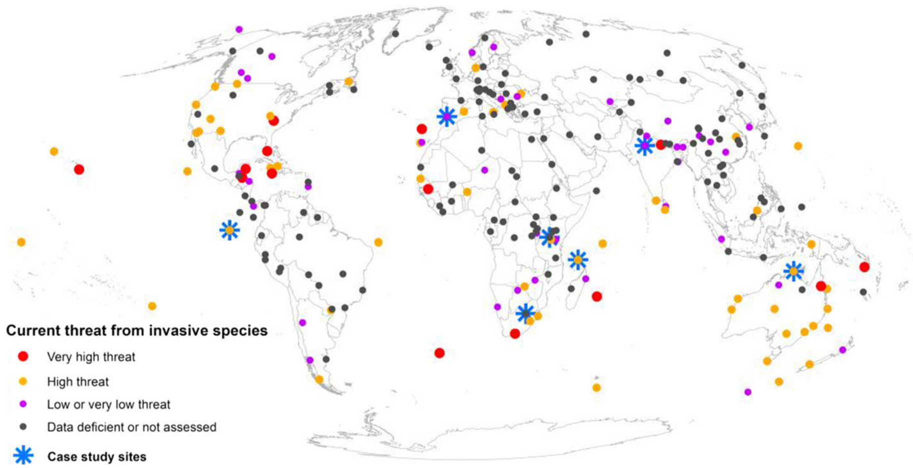

Fig. 1 Locations of the 241 natural and mixed World Heritage Sites (WHS inscribed as of early June 2018), and the seven case studies presented in this paper. The overall threat level from invasive alien species is based on data and categories used for the last IUCN World Heritage Outlook report (Osipova et al. 2017); see https://worldheritageoutlook.iucn.org/more/understanding-ratings for descriptions of WHS categories (NB: this is not based on our new framework). The case studies were Aldabra Atoll (Seychelles, tropical island with terrestrial and marine components), Doñana National Park (Spain, Mediterranean biome, wetlands and marine components), Galapagos Islands (Ecuador, over 100 arid to sub-tropical islands with terrestrial and marine components), Kakadu National Park (Australia, primarily savanna but including small patches of other biomes), Keoladeo National Park (India, broadleaf forests and wetlands), Serengeti National Park (Tanzania, savanna) and Vredefort Dome (South Africa, grasslands and savanna)

previously been identified as having high IAS threat levels, and four sites were previously listed as having no, low or medium threat levels. This gave us a broad range of contexts, to test the applicability of the framework. We collated information for our case studies from unpublished works and peer-reviewed and grey literature. In addition, many local researchers and managers working in, or knowledgeable on, specific WHS were consulted to obtain additional information or helped to write up the case studies.

Results

We present findings from the two components of this study: the review of past monitoring of the threat and management of IAS in WHS, and the introduction and application of the new monitoring and reporting framework.

A review of biological invasions and their management in World Heritage Sites globally

The overall presence of invasive alien species in World Heritage Sites

The data from the reviewed IUCN and UNESCO documents indicated that just over half (128; 53%) of all 241 WHS were explicitly or implicitly reported to be impacted by IAS (Fig. 1). This includes 119 WHS that are formally listed as being threatened by IAS in the IUCN World Heritage Outlook data, although many assessments make no further mention of any threatening species or their impacts (Fig. 2). For another nine WHS, IUCN and UNESCO documents mention the occurrence of known high impact IAS within their borders (e.g. *Dreissena polymorpha, Lantana camara*, *Opuntia* spp., *Prosopis juliflora*, and *Sus scrofa*), although IAS are not formally listed as a threat to these sites, suggesting inconsistency in reporting and threat categorisation.

For those WHS that formally listed IAS as a threat (119 WHS), ~ 80% explicitly named at least one IAS (Fig. 2), while the rest made no mention of a single invasive

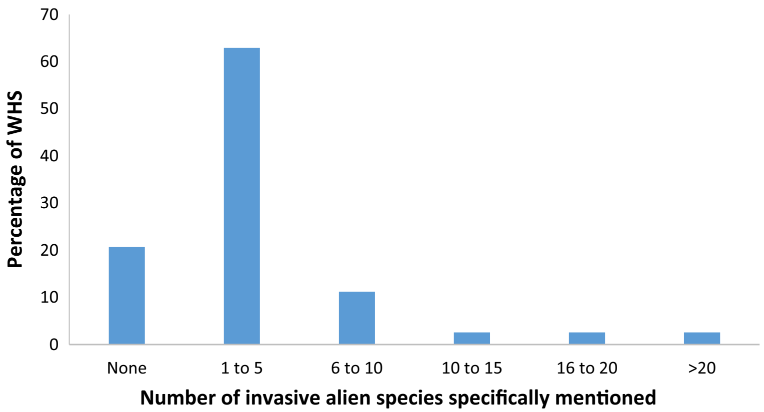

Fig. 2 Number of alien and/or invasive alien species specifically mentioned per natural and mixed World Heritage Site for those sites explicitly listed as being threatened by IAS (119 of 241) in the last World Heritage Outlook report (Osipova et al. 2017). This information was extracted from IUCN World Heritage Outlook data and the reviewed IUCN and UNESCO documents

species. Of those that mentioned IAS, just over a third listed only one species. Only 22 WHS specifically reported more than five alien or invasive species, of which only three sites named more than 20: Namib Sand Sea (Namibia) with 27, Gondwana Rainforests (Australia) and Socotra Archipelago (Yemen) with 24 each, athough the numbers for Socotra might be an overestiamte. Based on similar research from other PAs, if fewer than five species are reported to pose major threats it is likely due to under-reporting (Shackleton et al. 2020). Only seven WHS reported estimates of the total number of alien species occurring within their boundaries, which ranged from over 500 (Wet Tropics of Queensland in Australia), to 52 (Wadden Sea in Denmark, Germany and the Netherlands,—of which six are highly threatening).

Invasive alien species and their impacts mentioned in World Heritage Sites

In total, 290 different species/taxa were identified in the UNESCO and IUCN documents that were reviewed for all 241 WHS. These invasive taxa represented several different functional groups (Fig. 1 in Supplementary file 3). The most commonly reported functional group of IAS in WHS was land mammals, followed by trees, and then several other plant groups. Reporting on other taxonomic and functional groups in WHS was low, likely representing a common bias in research and monitoring in PAs (Shackleton et al. 2020), despite many of these "under-represented" functional groups having species with high impacts.

The three most commonly mentioned invasive alien taxa across all WHS were *Rattus* spp., *Felis catus* and *Capra hircus* (Table 1 in Supplementary file 3). They have been reported in many WHS globally, and cause severe problems for biodiversity, particularly on islands where they have driven extinctions of native species (e.g. Donlan et al. 2007; Duffy and Capece 2012; Dawson et al. 2014; Harper and Bunbury 2015). *Sus scrofa, Mus musculus*, and *Oryctolagus cuniculus* are other land mammals that are commonly reported as threats in WHS and have several major impacts on biodiversity and ecosystem function (e.g. Koichi et al. 2013; Saunders et al. 2013; Dawson et al. 2014).

The most commonly mentioned invasive alien plant was *Lantana camara* (Table 1 in Supplementry file 3), which negatively affects biodiversity and ecosystems in several WHS (e.g. Day et al. 2003; Aravind et al. 2010; Turner and Downey 2010; Shackleton et al. 2020). *Chromolaena odorata, Eichhornia crassipes, Mimosa pigra*, *Prosopis juliflora,* and *Psidium guajava*, which have similar impacts to *L. camara*, are also mentioned as present in many WHS (e.g. Cowie and Werner 1993; Foxcroft et al. 2013; Shackleton et al. 2020).

Other commonly listed IAS, from other taxonomic groups, with high impacts in WHS include: *Oncorhynchus mykiss*, *Phytophthora cinnamomi*, *Dreissena polymorpha* and *Linepithema humile* (e.g. Witt et al. 2004; Karssing et al. 2012; Rivers-Moore et al. 2013; Scarlett 2015) (Table 1 in Supplementary file 3). Mentions of other invasive taxa, such as birds, reptiles or amphibians, marine fish, and others were not common (Fig. 1 in Supplementary file 3).

Management of biological invasions in World Heritage Sites

Reporting on the management of biological invasions within WHS was often deficient in the UNESCO and IUCN documents that were reviewed. For 40% (48 of 119) of WHS with IAS formally listed as a threat, no information was available, or no mention was made of

Table 1 Evidence of attempted management and management plans for invasive alien species (IAS) in the 119 natural and mixed World Heritage Sites (WHS) reported as being threatened by IAS

	Yes		No		Ongoing/ mixed		Not reported	
	#	%	#	%	#	%	#	%
IAS management attempted in WHS (n = 119)	59	50	12	10	n/a	n/a	48	40
Management plan for IAS (n = 119)	44	37	14	12	n/a	n/a	61	51
Management success (*for those that have attempted management, n = 59)*	19	32	2	3	18	31	20	34

For management success, "Yes" indicates that the WHS has reported eradications and/or other successful control efforts

management, even though sites potentially have been conducting control activities (Table 1). Only 10% (12 of 119) of WHS with IAS present indicated no control interventions (Table 1), although this is likely to be higher, as many did not provide any information. Half of WHS with IAS listed as a threat (59 of 119 WHS) reported attempts to control IAS. Most of these are committed to long-term control, however, some sites mentioned opportunistic management based on funding availability.

In general, outcomes of IAS control were not elaborated on, with only 34% (20 of 59) of WHS providing any information on the success or failure of IAS management. However, some sites did highlight management successes (32%, or 19 of 59); and two sites mentioned that, despite management, the situation was getting worse (Table 1). Successes included containment and impact reduction of IAS (e.g. Pitons Managment Area and Kakadu), with some sites even achieving multiple eradications (e.g. Macquarie Island, Fraser Island and Galapagos Islands). It was difficult to assess management success or failure in some cases, as programmes were still underway (Table 1). Many WHS for which IAS are listed as a threat, and which are managing IAS, have broad-scale and/or species-specific IAS management plans (37%; 44 of 119), while some (12%) have informal approaches to management with no specific plan. Information on IAS management plans was lacking for half of the WHS with IAS (Table 1).

Only 10% of WHS (12 of 119), most of them islands, mention having biosecurity measures in place to prevent new introductions, but details are lacking for most of these. For control of IAS populations, physical interventions that involved cutting or digging out plants, and shooting or trapping animals, was by far the most common approach reported. Only nine WHS report the use of chemical control, always in combination with other approaches. Cultural control and control through utilisation are less traditional management techniques and are implemented in a few WHS (e.g. Keoladeo where authorities allow villages into the site to harvest *P. juliflora* as a control option and fishing of invasive *Pterois volitans* in the Belize Barrier Reef Reserve System). A few sites also mention the presence of biological control agents (e.g. Galapagos, Glacier International Peace Park, and Kakadu). The Pitons Management Area (Saint Lucia) is managing *Callisia fragrans* and *Tradescantia zebrina* using a volunteer programme which is showing signs of reducing spread. Some WHS have an integrated approach to management, using a combination of control techniques and approaches to maximise management effectiveness (e.g. Kakadu) (Paynter and Flanagan 2004).

A new framework for monitoring and reporting the presence, impacts and management of biological invasions in natural WHS and protected areas

Our review discussed above (e.g. Figure 2; Table 1) revealed obvious challenges to meaningful monitoring and reporting of biological invasions and their management within WHS, which is likely to also be a problem with other categories of PAs. Although substantial effort has been devoted to monitoring biological invasions and other threats in WHS (Osipova et al. 2017; IUCN 2018), essential data are often no reported in the IUCN and UNESCO databases, or it is inconsistent, or not detailed enough to be meaningful. As a result, there is a lack of usable information on which to base detailed and robust assessments of temporal changes to levels of threat or progress in the management of IAS in WHS. We therefore propose a framework (Fig. 3) to guide holistic and standardised monitoring and reporting of biological invasions. This will facilitate the provision of meaningful data, which would permit better spatial and temporal analysis and comparisons, aiding scientific understanding as well as policy and management development and implementation in PAs globally.

The newly proposed monitoring and reporting framework

The framework comprises three key components relating to: monitoring and reporting on the *current status* of biological invasions and their management; *predictions* regarding future threats and management needs; and an *assessment* which culminates in assigning an overall threat score for the site based on the availability and status of knowledge from the preceding components of the framework (Fig. 3).

The first step of the process is to identify the *current status* of biological invasions and their management (see Supplementary file 1 for more details and instructions for applying the framework). This step focuses particularly on: (1) assessing pathways of introduction using the CBD framework; (2) reporting the total number of alien species present (broken down, if possible, into total numbers for different taxa and separating out those that are

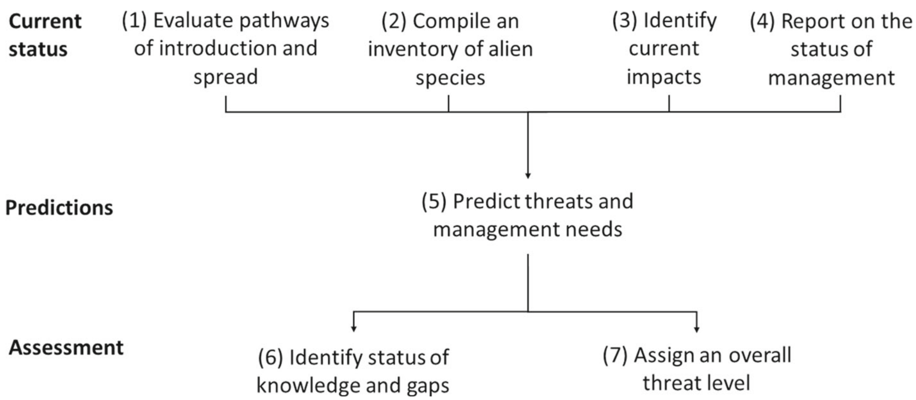

Fig. 3 A proposed framework for monitoring and reporting on biological invasions and their management in natural and mixed World Heritage Sites globally. The result of the process (i.e. stage 7) is that each site is given an overall threat level ("very high", "high", "moderate", "low", or "data deficient"). Instructions on how to implement the framework are given in Supplementary file 1, and case study examples of its application are in Supplementary file 2

alien vs invasive), with this information potentially based on various sources of ex situ or in situ information; (3) listing harmful IAS and highlighting their impacts [using either local evidence, global evidence or EICAT scores (IUCN, in press)]; and (4) an assessment of management interventions for the site (cf. Van Wilgen and Wilson 2018). For component (4), reporting should state whether any IAS management is in place at the site. If yes, each approach should be commented on, including: prevention initiatives, incursion response activities, attempts at eradication or containment, and asset protection measures. This will include a discussion of the various control techniques used (e.g. biological, manual, chemical control, etc.), as well as the effectiveness of the techniques and the degree to which approaches have achieved the stated management goals. Any barriers to management should also be identified here, and, if possible, details of budgets for control should also be provided. For management, the collected evidence from the previous components should be evaluated, and an overall management status should be assigned to the site: highly effective, effective, some concern, serious concern, or data deficient (Table 2).

Following the first step of the framework, which assesses *current status* (components 1–4), the next component (5) relates to *predictions* and assesses future threats posed by biological invasions and likely future management needs. This includes identifying and listing alien species that are likely to be introduced in the future or that are present and likely to increases in abundance and extent; highlighting potential future impacts; and identifying and listing future management needs. This can draw on various data and approaches, including suitability models and expert opinion. Components 1–5 should also include expert assessments of trends over time for each of these factors (i.e. for component 3: the assessor should indicate whether they believe that the overall impacts of IAS in the site are: increasing, decreasing, stable, or unknown over time).

The final part of the framework relates to *assessment*. The first part, component (6), deliberates on the status of knowledge and assesses the level of confidence in the information provided in components 1–5 ranking them as either high, moderate, low or data deficient. The second part, component (7), draws on all the proceeding information to assign an overall threat level (very high threat, high threat, moderate threat, low threat

Table 2 Categorisation of the effectiveness of management, linked to those alredy used by the IUNC (IUCN 2018)

Category	Category description
Highly effective	Successful management is reducing the overall threat and impact of biological invasions and ensures the values and integrity of the site in the long term. There is a guarantee of adequate and sustained funding for management and management implementation
Effective	Management has reduced the threat and impacts of most IAS but more effort is needed to ensure the values and integrity of the site, in the long term. Funding for management in the long run is almost certain and adequate
Some concern	Management is taking place but is not effectively reducing the threat and impact of IAS—this could affect the values and integrity of the site in the long term—adaptive management could potentially improve the situation. There is funding but it might not be adequate or sustained in the long run
Serious concern	No management interventions in place, or management interventions are not reducing the threat and impact (spread) of IAS and the values and integrity of the site are in jeopardy in the future. There is no funding for management
Data deficient	No information available

Table 3 Categorisation of overall threat levels posed by biological invasions to World Heritage Sites as per the proposed monitoring and reporting framework (Fig. 3)

Very high threat	Invasive alien species have or are likely to induce irreversible changes to community structure and ecosystem services with no likelihood of them returning to their original state resulting in irreversible damage to the values and integrity of the site even with effective management
High threat	Can cause changes to community composition, substantially alter the supply of ecosystem services and thus poses a substantial threat to the values and integrity of the site but can be avoided or reversed with highly effective management
Moderate threat	May cause minor changes in community composition and reduce the supply of some ecosystem services resulting in small-scale (localised) impacts but not fundamentally alter them. These impacts are reversible through management, or impacts will not raise substantially without management and therefore do not post significant threats to the values and integrity of the site
Low threat	May alter individual species fitness but has limited effects on ecosystem services. The threats posed to the values and integrity of the site are limited. Management could remove these species altogether or absence of management would not raise the threat posed
Data deficient	Not enough information available

or data deficient) for the site (Table 3). More in-depth details and guidelines on how to apply the framework appear in the supplementary material (Supplementary file1).

Application of the newly proposed framework at seven World Heritage Sites

Using the seven case studies with highly different social–ecological settings, we highlight the value of the new framework to allow for improved reporting of PAs. Detailed write-ups for each WHS after applying the framework (Fig. 3) are provided in the Supplementary file 2.

Applying the framework has yielded more information than past monitoring initiatives. For example, the IAS threat level indicated in the 2017 IUCN World Heritage Outlook for the Serengeti, Keoladeo, Doñana, and the Vredefort Dome sites was "data deficient" or "low threat" or "not listed", whereas all of these WHS are now categorised as facing moderate to high threats from biological invasions based on our assessment informed by the framework (Table 4: Supplementary file 2).

Serious threats as a result of IAS were reported for some sites in the IUCN and UNESCO documents based on previous monitoring, but detailed and accurate information was missing, for example in the case of the Galapagos Islands (Table 4). The additional data provided for the Galapagos Islands sheds light on the threats and management of IAS at the site and suggests a very high threat instead of a high threat as indicated in the 2017 IUCN World Heritage Outlook (Table 4). Interestingly, the application of the in-depth framework has also highlighted some successes, where through effective management (eradications), the overall number of IAS has decreased on Aldabra.

Application of the framework more than doubled the number of IAS reported for all sites except for Aldabra, which has had an overall decrease in IAS through effective eradication campaigns (Table 4). Our review also highlighted that several globally important IAS are present in many of the case study WHS but have not yet been reported in UNESCO and IUCN databases and documents. These include species such as *Carpobrotus edulis* and *Opuntia ficus-indica* in Doñana National Park; *Arundo donax, Eucalyptus* spp.

Table 4 In-depth case studies of invasive alien species (IAS) and their management in seven World Heritage Sites based on the reporting framework proposed in this paper (see Fig. 3; and Supplementary files 1 and 2 for full details)

Site name (country)	# of IAS listed based on assessments using the new framework (# of IAS previously listed)	List of IAS in each site with the highest threat based on new framework	Management success based on this study	Overall threat level based on in-depth assessments made in this study (threat levels according to the 2017 World Heritage Outlook)
Aldabra Atoll (Seychelles)	5 (7)	*Rattus rattus; Felis catus Casuarina equisetifolia; Icerya seychellarum; Stachytarpheta jamaicensis*	Effective	High threat (High threat)
Doñana National Park (Spain)	75 (5)	*Azolla filiculoides; Eucalyptus camaldulensis; Carpobrotus edulis; Cyprinus carpio; Eriocheir sinensis; Linepithema humile; Micropterus salmoides; Procambarus clarkii*	Some concern	High threat (Low threat)
Galapagos Islands (Ecuador)	60 (12)	*Cedrela odorata; Felis catus; Rattus norvegicus, Rattus rattus; Philornis downsi; Polistes versicolor; Psidium guajava; Solenopsis geminata; Rubus niveus; Wasmannia auropunctata*	Some concern	Very high threat (High threat)
Kakadu National Park (Australia)	60 (19)	*Andropogon gayanus; Salvinia molesta*; *Mimosa pigra; Hymenachne amplexicaulis*; *Pennisetum polystachion; Themeda quadrivalvis; Jatropha gossypiifolia*	Some concern	High threat (High threat)
Keoladeo National Park (India)	14 (5)	*Bos taurus; Clarisa gariepinus; Eichhornia crassipes; Lantana camara; Parapoynx diminutalis; Paspalum distichum; Prosopis juliflora*	Serious concern	High threat (Low threat)
Serengeti National Park (Tanzania)	23 (4)	*Opuntia stricta; Lantana camara; Parthenium hysterophorus; Pistia stratiotes; Opuntia monacantha: Chromolaena odorata*	Serious concern	High threat (data deficient)
Vredefort Dome (South Africa)	44 (0)	*Arundo donax; Cestrum laevigatum; Cyprinus carpio; Eichhornia crassipes; Eucalyptus* spp.; *Gleditsia triacanthos; Micropterus salmoides; Myriophyllum aquaticum; Opuntia* spp.; *Tamarix ramosissima*	Effective	Moderate threat (threat level not listed)

and *Eichhornia crassipes* in Vredefort Dome; and *Lantana camara* and *Parthenium hysterophorus* in Serengeti National Park. All of these taxa are amongst the 49 worst IAS in PAs globally according to Foxcroft et al. (2017) and are threatening IAS in other WHS (Supplementary file 2, 3). After applying the framework, further insights into management successes and challenges were uncovered, which could be beneficial for guiding future control. However, many sites still face challenges, which are important to acknowledge to guide future policy and control (Table 4; Supplementary file 2).

Discussion

Natural and mixed WHS and other PAs face major and growing threats from biological invasions (Usher 1988; Foxcroft et al. 2013, 2017; Osipova et al. 2017; Witt et al. 2017; Liu et al. 2020; Shackleton et al. 2020) (Fig. 1; Table 4). IAS threaten the outstanding values of PAs and WHS by impacting on biodiversity and the delivery of ecosystem services (e.g. García Murillo et al. 2007; Jäger et al. 2009; Dawson et al. 2014; Mukherjee et al. 2017). IAS are also a financial burden, as costs for IAS management can be extremely high (van Wilgen et al. 2016; Shackleton et al. 2020). It is, therefore, crucial to monitor and understand the status of biological invasions and their management in PAs.

Our research shows that although IAS are recognised as a major risk to WHS globally, detailed knowledge and reporting on their threats and management is highly variable, and are scarce for many sites, despite the long-term monitoring via IUCN and UNESCO mechanisms (Fig. 2; Table 1). For example, for most WHS where IAS are listed as a threat, little is known about which species are present, what impacts they are having, or what interventions are being applied (Fig. 2; Table 1). This might be due to a lack of knowledge and capacity, inconsistent reporting, and/or the lack of a standardized procedure for reporting. To address the issues relating monitoring and reporting, we proposed a new framework (Fig. 3; Supplementary file 1) and tested this using seven diverse case studies (Table 4; Supplementary file 2). Recent publications highlight the importance of well-designed monitoring and reporting procedures for IAS that facilitate comparisons over space and time (e.g. Latombe et al. 2017; Wilson et al. 2018; Pergl et al. 2020). Standardised long-term monitoring of IAS and their management in WHS and other PAs would help to realise the vision of robust monitoring of biological invasions globally (Latombe et al. 2017) to guide adaptive management, aid with policy development, and improve the understanding of invasion dynamics.

A standardised monitoring and reporting mechanism for biological invasions in World Heritage Sites

The new seven component reporting and monitoring framework (Fig. 3) should complement the existing monitoring processes. It could also serve as a guide for future assessments and reporting of IAS in all PAs globally as it draws on other widely applied schemes such as the CBD pathway framework and the EICAT assessment framework (e.g. see Blackburn et al. 2014; CBD 2014; Hawkins et al. 2015; Harrower et al. 2017; Osipova et al. 2017; Wilson et al. 2018). Use of this framework would improve the consistency, comparability and overall value of future reporting on IAS threats and management. Over time and with further testing, the IUCN and UNESCO could adapt the framework to develop a finer set of indicators and revise it accordingly (see Wilson et al. 2018).

We suggest that all PAs should report on pathways of introduction to guide pre-emptive management (Hulme 2009; Saul et al. 2007; Foxcroft et al. 2019). Pathway assessments are lacking for most PAs but form the basis for effective biosecurity interventions and surveillance (Colunga-Garcia et al. 2013; Toral-Granda et al. 2017) and can be very useful to guide management and understand future impacts (Foxcroft et al. 2019). Such information will help managers to monitor relevant areas, saving time and money. It could also help to prevent new introductions and to monitor problematic species, which could be quickly eradicated before they establish (Meyerson and Reaser 2002; Keller et al. 2007; Wilson et al. 2013). For example, Hemp (2008) reports that the increased level of hiking in the Kilimanjaro National Park has increased the introduction and spread of numerous invasive plants. Introduction of ornamental plants in lodges and staff villages has led to biological invasions in many PAs (Foxcroft et al. 2008). In Keoladeo, the purposeful introduction of *P. juliflora* to provide provisioning services to local communities has become a major issue (Mukherjee et al. 2017), and the same mistake was repeated more recently by introducing *Clarias gariepinus* to promote aquaculture (Supplementary file 2). The Kakadu site is threatened by natural dispersal of *Rhinella marina* from other areas (Kearney et al. 2008) and Galapagos faces major challenges from stowaways and transport contaminants (Toral-Granda et al. 2017) to a greater extent than other island protected areas like Aldabra (Supplementary file 2). Understanding these pathways can lead to the implementation of improved control methods, such as disinfecting hikers' equipment and prohibiting the planting of non-native species at lodges, disinfecting transported goods. Similarly, anticipatory monitoring could be implemented to prevent future introductions and spread.

Producing lists of all alien and invasive alien species present is important for management and a key target for monitoring (McGeoch et al. 2012). Such lists are baseline indicators that track changes in threat or the implementation of effective management over time (Fig. 3; Table 4). For example, Aldabra Atoll shows a decrease in the number of IAS listed due to effective eradications, showing great management success. Since current UNESCO and IUCN reporting mechanisms do not stipulate the provision of full species lists, listing of alien species varies considerably between WHS, and many sites may still lack the necessary data and research to generate accurate lists. A large proportion (21%) of WHS that specifically highlighted IAS as a threat did not indicate the number of IAS present, and many of these did not name a single IAS (Fig. 2). Lists can be derived using in situ or ex situ information and combining several different approaches, such as literature searches, GIS-based techniques, and ground-based surveys. Lists of IAS need to be carefully reviewed by experts and should be standardised as much as possible (McGeoch et al. 2012; Latombe et al. 2019; Groom et al. 2019). Funding should be made available to conduct surveys at all under-resourced WHS to inform the reactive "state of conservation" assessments undertaken by UNESCO and IUCN. Other options could also be the use of monitoring based on citizen science (Devictor et al. 2010; Mannino and Balistreri, 2018). Several WHS already have projects on iNaturalist, such as, the Everglades National Park in the USA (https://www.inaturalist.org/places/everglades-national-park-world-heritage-site) and iSimangaliso Wetland Park in South Africa (https://www.inaturalist.org/places/isimangaliso-wetland-park-world-heritage-site). Initiating such projects for all WHS would be an important first step towards providing up-to-date and freely accessible lists that apply standardised taxonomy, and would provide the means for flagging new incursions to allow for rapid response.

High priority IAS (top 10 or more) and their impacts should be specifically mentioned in the text or highlighted in some way. Scientific names, rather than common names, should be used. This was not common practice in previous reporting in IUCN and UNESCO documents, where many IAS were reported using only common names which leads to confusion in some cases. Although there is growing evidence that many IAS have major impacts in PAs (Foxcroft et al. 2013, 2017), including WHS (e.g. see citations in Sect. 3.1.2, and in the detailed case studies in Supplementary file 2), there is a need for more detailed information on how biodiversity and ecosystems are affected. Very few WHS documents provided evidence or mentioned actual impacts. Research to document and provide objective quantification of negative impacts of invasions could be used to help secure funding for management and therfore greatly needed. Assessments of impact can be done by local researchers in PAs or through approaches such as impact scoring (e.g. EICAT or SEICAT) based on global literature (Blackburn et al. 2014; Hawkins et al. 2015; Bacher et al. 2018).

It is also important to review and provide information on past and current management practices to assess successes and failures to inform future management planning (Shackleton et al. 2020). Documents for a large proportion of WHS that specifically list IAS as a threat make no mention of management (Table 1) Knowledge and reporting on management history is crucial for understanding changes in threat levels over time and for assessing capacity and success rates in responding to threats (Shackleton et al. 2020). Major successes and failures should be highlighted (Fig. 3; Supplementary files 1, 2). Reporting should note whether management plans are in place, and the key goals of plans should be stated. Summaries should discuss different approaches for preventive biosecurity measures, management goals such as eradication and impact reduction, and control methods used such as biological, mechanical, chemical control and utilisation (it must be noted that promoting utilisation can have limited effect on invasions and can be controversial in PAs). Information on control plans and techniques was lacking in previous reporting (Table 1) but useful information was collected through the new reporting framework (see Supplementary file 2).

As part of reporting and monitoring, future issues need to be identified. This can help to guide strategic planning of management interventions. Tools that can be used include horizon scanning or modelling approaches, pathway analysis or simple tools to create watch lists (Gasso et al. 2012; Faulkner et al. 2014; Roy et al. 2014; Toral-Granda et al. 2017; Witt et al. 2017). Future needs for management should also be highlighted to aid with planning and prioritisation and helping to ensure successful control programes (Downey 2010; van Wilgen et al. 2011; Shackleton et al. 2017; te Beest et al. 2017). When reporting on invasions and their management, it is important that information on the status of knowledge and uncertainty is provided to help guide future comparative analyses and research (Wilson et al. 2018; Latombe et al. 2019). Based on a good overview of threats, management and knowledge levels, an overall threat score can be assigned based on clearly defined criteria (Table 3; Supplementary files 1, 2).

The seven case studies conducted using the new framework (Table 4; Supplementary file 2) show that this proposed framework and approach is useful in guiding and standardising data collection. Application of the framework resulted in many case study WHS changing from being listed as “data deficient or low threat” to being listed as having “moderate to high threat” levels (Table 4). Better collation of data also allows successes in managing invasions that were not highlighted before to be uncovered, as in the case of the Aldabra Atoll (Table 4). Like other success cases of management in PAs (te Beest et al. 2017; Shackleton et al. 2020), much can be learned from these cases to guide management elsewhere.

Application of this framework in WHS and other PAs would help facilitate comparisons and the sharing of best practices between sites and help to guide the allocation and prioritisation of funding to manage IAS. Furthermore, application of the framework could provide the basis for a freely available global information system with an inventory of IAS threats to WHS and other PAs. This information could be included on the existing UNESCO and IUCN websites, in the online portal for the IUCN World Heritage Outlook assessments, or on platforms such as the Global Invasive Species Database (GISD; https://www.iucngisd.org/gisd/) and CABI's Invasive Species Compendium (https://www.cabi.org/isc/). We suggest that reports could be provided every three years and the framework could be modified as more knowledge is gained and following further testing of its application in practice in different contexts. This would be a major step towards the vision of robust monitoring of biological invasions globally (Latombe et al. 2017) and is greatly needed to guide future research, policies and management pertaining to biological invasions.

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Author contributions Data are available in the supplementary material and on IUCN and UNESCO websites. BB, DMR and RTS conceived the study. BB provided data and did the mapping. LEW and RTS conducted the review. JRUW and RTS developed the monitoring framework, with contributions from all other authors. RTS, LEW, NB, HJ, CS, and ABRW conducted the case study data collection and write up with further comments from all other authors. RTS wrote the first draft of the manuscript with input from all other authors.

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References

Angassa A (2005) The ecological impact of bush encroachment on the yield of grasses in Borana rangeland ecosystem. Afr J Ecol 43:14–20

Aravind NA, Rao D, Ganeshaiah KN, Shaanker RU, Poulsen JG (2010) Impact of the invasive plant, *Lantana camara*, on bird assemblages at Male Mahadeshwara Reserve Forest, South India. Tropical Ecol 51:325–338

Bacher S et al (2018) Socio-economic impact classification of alien taxa (SEICAT). Meth Ecol Evol 9:159–168

Bellard C, Cassey P, Blackburn TM (2016) Alien species as a driver of recent extinctions. Biol Lett 12:20150623

Bertzky B, Engels B, Howard P, Nozawa C, Obura D, Seely M, Strahm W, Thorsell J (2014) World heritage and species: safe havens for wildlife? World Heritage 73:28–37

Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Vilà M, Wilson JRU, Winter M, Genovesi P, Bacher S (2014) A unified classification of alien species based on the magnitude of their environmental impacts. PLoS Biol 12:e1001850

Bomanowska A, Adamowski W, Kirpluk I, Rewicz OA (2019) Invasive alien plants in Polish national parks: threats to species diversity. PeerJ 7:e8034

Bradshaw CJA, Field IC, Bowman DMJS, Haynes C, Brook BW (2007) Current and future threats from non-indigenous animal species in northern Australia: a spotlight on World Heritage Area Kakadu National Park. Wildl Res 34:419–436

Brook BW, Sodhi NS, Bradshaw CJ (2008) Synergies among extinction drivers under global change. Trends Ecol Evol 23:453–460

Butchart SH et al (2010) Global biodiversity: indicators of recent declines. Science 328:1164–1168

[CBD] Convention on Biological Diversity (2014) Pathways of introduction of invasive species, their prioritization, and management. UNEP/CBD/SBSTTA/18/1

Chape S, Harrison J, Spalding M, Lysenko I (2005) Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. Philos Trans R Soc B 360:443–455

Clavero M, García-Berthou E (2005) Invasive species are a leading cause of animal extinctions. Trends Ecol Evol 20:110

Colunga-Garcia M, Haack RA, Magarey RD, Borchert DM (2013) Understanding trade pathways to target biosecurity surveillance. NeoBiota 18:103–118

Cowie ID, Werner PA (1993) Alien plant species invasive in Kakadu National Park, tropical northern Australia. Biol Conserv 63:127–135

Dawson J, Oppel S, Cuthbert RJ, Holmes N, Brid JP, Butchart SHM, Spatz DR, Tershy B (2014) Prioritizing islands for the eradication of invasive vertebrates in the United Kingdom overseas territories. Conserv Biol 29:143–153

Day M, Wiley CJ, Playford J, Zalucki MP (2003) Lantana: current management status and future prospects. ACIAR, Canberra, ACT

Devictor V, Whittaker RJ, Beltrame C (2010) Beyond scarcity: citizen science programmes as useful tools for conservation biogeography. Divers Distrib 16:354–362

Donlan CJ, Campbell K, Cabrera W, Lavoie C, Carrion V, Cruz F (2007) Recovery of the Galápagos Rail (*Laterallus spilonotus*) following the removal of invasive mammals. Biol Conserv 138:520–524

Downey PO (2010) Managing widespread, alien plant species to ensure biodiversity conservation: a case study using an 11-step planning process. Invasive Plant Sci Manage 3:451–461

Downey PO, Richardson DM (2016) Alien plant invasions and native plant extinctions: a six-threshold framework. AoB PLANTS 8:plw047

Dudley N (2008) Guidelines for applying protected area management categories. IUCN, Gland

Duffy DC, Capece P (2012) Biology and impacts of Pacific Island invasive species. 7. The domestic cat (*Felis catus*). Pac Sci 66:173–213

Egoh B, Rouget M, Reyers B, Knight AT, Cowling RM, van Jaarsveld AS, Welz A (2007) Integrating ecosystem services into conservation assessments: a review. Ecol Econ 63:714–721

Eldridge DJ, Bowker MA, Maestre FT, Roger E, Whitford RJF (2011) Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis. Ecol Lett 14:709–722

Essl F, Dullinger S, Rabitsch W, Hulme PE, Hülber K, Jarošík V, Kleinbauer I, Krausmann F, Kühn I, Nentwig W, Vilà M (2011) Socioeconomic legacy yields an invasion debt. Proc Natl Acad Sci USA 108:203–207

Faulkner KT, Robertson MP, Roget M, Wilson JRU (2014) A simple, rapid methodology for developing invasive species watch lists. Biol Conserv 179:25–32

Foxcroft LC, Richardson DM, Wilson JRU (2008) Ornamental plants as invasive aliens: problems and solutions in Kruger National Park, South Africa. Environ Manage 41:32–51
Foxcroft LC, Pyšek P, Richardson DM, Genovesi P (2013) Plant invasions in protected areas: patterns, problems and challenges. Invading nature series Volume 7. Springer, Berlin
Foxcroft LC, Pyšek P, Richardson DM, Genovesi P, MacFadyen S (2017) Plant invasions in protected areas: progress and priorities. Biol Invasions 19:1353–1378
Foxcroft LC, Spear D, van Wilgen NJ, McGeoch MA (2019) Assessing the association between pathways of alien plant invaders and their impacts in protected areas. NeoBiota 43:1–25
García Murillo P, Fernández Zamudio MDR, Cirujano Bracamonte S, Sousa Martín A, Espinar JM (2007) The invasion of Doñana National Park (SW Spain) by the mosquito fern (Azolla filiculoides Lam). Limnetica 26:43–250
Gassó N, Thuiller W, Pino J, Vilà M (2012) Potential distribution range of invasive plant species in Spain. NeoBiota 12:25–40
Groom Q, Desmet P, Reyserhove L, Adriaens T, Oldoni D, Vanderhoeven S, Baskauf SJ, Chapman A, McGeoch M, Walls R, Wieczorek J, Wilson JRU, Zermoglio PFF, Simpson A (2019) Improving Darwin Core for research and management of alien species. Biodivers Inf Sci Stand 3:e38084
Harper GA, Bunbury N (2015) Invasive rats on tropical islands: their population biology and impacts on native species. Glob Ecol Conserv 3:607–627
Harrower CA, Scalera R, Pagad S, Schönrogge K Roy HE (2017) Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission.
Hawkins CL, Bacher S, Essl F, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Vila M, Wilson JRU, Genovesi P, Blackburn T (2015) Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT). Divers Distrib 21:1360–1363
Hejda M, Pyšek P, Jarošík V (2009) Impact of invasive plants on the species richness, diversity and composition of invaded communities. J Ecol 97:393–403
Hemp A (2008) Introduced plants on Kilimanjaro: tourism and its impact. Plant Ecol 197:17–29
Hernandez-Enriquez O, Alvarez R, Morelli F, Bastida F, Menendez CD (2012) Low-impact chemical weed control techniques in UNESCO World Heritage Sites of Cuba. Commun Agric Appl Biol Sci 77:387–393
Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalisation. J Appl Ecol 46:10–18
Hulme PE, Bacher S, Kenis M, Klotz S, Kuhn I, Minchin D, Nentwig W, Olenin S, Panov V, Pergl J, Pyšek P, Roques A, Sol D, Vila SW (2008) Grasping at the routes of biological invasions: a framework for integrating pathways into policy. J Appl Ecol 45:403–414
IUCN (2000) Guidelines for the Prevention of Biodiversity Loss Caused by Alien Invasive Species. Approved by the 51st Meeting of the IUCN Council, Gland Switzerland
IUCN (2017) Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission
IUCN (2018) World Heritage Outlook: Understanding ratings [On-line], January 2018. IUCN, Gland, Switzerland and Cambridge, UK. https://www.worldheritageoutlook.iucn.org/
IUCN (in press) IUCN EICAT categories and criteria. The environmental impact classification for alien taxa, 1st edn. IUCN, Gland
Jäger H, Kowarik I, Tye A (2009) Destruction without extinction: long-term impacts of an invasive tree species on Galápagos highland vegetation. J Ecol 97:1252–1263
Jeschke JM et al (2014) Defining the impact of non-native species. Conserv Biol 28:1188–1194
Johnson CN, Balmford A, Brook BW, Buettel JC, Galetti M, Guangchun L, Wilmshurst JM (2017) Biodiversity losses and conservation responses in the Anthropocene. Science 356:270–275
Karssing RJ, Rivers-Moore NA, Slater K (2012) Influence of waterfalls on patterns of association between trout and Natal cascade frog *Hadromophryne natalensis* tadpoles in two headwater streams in the Ukhahlamba Drakensberg Park World Heritage Site, South Africa. Afr J Aquat Sci 37:107–112
Kearney M, Phillips BL, Tracy CR, Christian KA, Betts G, Porter WP (2008) Modelling species distributions without using species distributions: the cane toad in Australia under current and future climates. Ecography 31:423–434
Keller RP, Lodge DM, Finnoff DC (2007) Risk assessment for invasive species produces net bioeconomic benefits. Proc Natl Acad Sci USA 104:203–207
Koichi K, Cottrell A, Sangha KK, Gordon IJ (2013) What determines the acceptability of wildlife control methods? A case of feral pig management in the Wet Tropics World Heritage Area, Australia. Hum Dimens Wildl 18:97–108
Latombe G et al (2017) A vision for global monitoring of biological invasions. Biol Conserv 213:295–308

Latombe G, Canavan S, Hirsch H, Hui C, Kumschick S, Nsikani MM, Potgieter LJ, Saul WC, Turner SC, Wilson JRU, Richardson YFA (2019) A four-component classification of uncertainties in biological invasions: implications for management. Ecosphere 10:e02669

Liu X, Blackburn TM, Song T, Wang X, Huang C, Li Y (2020) Animal invaders threatern protected areas worldwide. Nat Comm 11:2892

Mannino AM, Balistreri P (2018) Citizen science: a successful tool for monitoring invasive alien species (IAS) in Marine Protected Areas. The case study of the Egadi Islands MPA (Tyrrhenian Sea, Italy). Biodiversity 19:42–48

McGeoch MA, Butchart SH, Spear D, Marais E, Kleynhans E, Symes A, Chanson J, Hoffmann M (2010) Global indicators of biological invasion: species, numbers, biodiversity impact and policy responses. Divers Distrib 16:95–108

McGeoch MA, Spear D, Kleynhans EJ, Marais E (2012) Uncertainty in invasive alien species listing. Ecol Appl 22:959–971

Meyerson LA, Reaser JK (2002) Biosecurity: moving toward a comprehensive approach: a comprehensive approach to biosecurity is necessary to minimize the risk of harm caused by non-native organisms to agriculture, the economy, the environment, and human health. Bioscience 52:593–600

Mukherjee A, Velankar AD, Kumara HN (2017) Invasive *Prosopis juliflora* replacing the native floral community over three decades: a case study of a World Heritage Site, Keoladeo National Park, India. Biodivers Conserv 26:2839–2856

Nauhton-Treves L, Holland MB, Brandon K (2005) The role of protected areas in conservation biodiversity and sustaining local livelihoods. Annu Rev Environ Resour 30:219–252

Osipova E, Shi Y, Kormos C, Shadie P, Zwahlen C, Badman T (2014) IUCN World Heritage Outlook 2014: a conservation assessment of all natural World Heritage sites. IUCN, Gland

Osipova E, Shadie P, Zwahlen C, Osti M, Shi Y, Kormos C, Bertzky B, Murai M, van Merm R, Badman T (2017) IUCN World Heritage Outlook 2: a conservation assessment of all natural World Heritage sites. IUCN, Gland

Padmanaba M, Tomlinson KW, Corlett HAC (2017) Alien plant invasions of protected areas in Java, Indonesia. Sci Rep 7:1–11

Paynter Q, Flanagan GJ (2004) Integrating herbicide and mechanical control treatments with fire and biological control to manage an invasive wetland shrub, *Mimosa pigra*. J Appl Ecol 41:615–629

Pejchar L, Mooney HA (2009) Invasive species, ecosystem services and human well-being. Trends Ecol Evol 24:497–504

Pergl J, Pyšek P, Essl F, Jeschke JM, Courchamp F, Geist J, Hejda M, Kowarik I, Mill A, Musseau C, Pipek P (2020) Need for routine tracking of biological invasions. Conserv Biol. https://doi.org/10.1111/cobi.13445

Richardson DM, Pyšek P, Rejmánek M, Barbour MG, Panetta FD, West CJ (2000) Naturalization and invasion of alien plants: concepts and definitions. Divers Distrib 6:93–107

Richardson DM, Pyšek P, Carlton JT (2011) A compendium of essential concepts and terminology in invasion ecology. In: Richardson DM (ed) Fifty years of invasion ecology. The legacy of Charles Elton. Wiley-Blackwell, Oxford, pp 409–420

Rivers-Moore NA, Fowles B, Karssing RJ (2013) Impacts of trout on aquatic macroinvertebrates in three Drakensberg rivers in KwaZulu-Natal, South Africa. Afr J Aquat Sci 38:93–99

Rouget M, Robertson MP, Wilson JR, Hui C, Essl F, Renteria JL, Richardson DM (2016) Invasion debt–Quantifying future biological invasions. Divers Distrib 22:445–456

Roy HE et al (2014) Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. Glob Change Biol 20:3859–3871

Saul WC, Roy HE, Booy O, Carnevali L, Chen HJ, Genovesi P, Harrower CA, Hulme PE, Pagad S, Jeschke PJ (2017) Assessing patterns in introduction pathways of alien species by linking major invasion data bases. J Appl Ecol 54:657–669

Saunders KM, Harrison JJ, Hodgson DA, de Jong R, Mauchle F, McMinn A (2013) Ecosystem impacts of feral rabbits on World Heritage sub-Antarctic Macquarie Island: a palaeoecological perspective. Anthropocene 3:1–8

Scarlett K, Daniel R, Shuttleworth LA, Roy B, Bishop TF, Guest DI (2015) Phytophthora in the Gondwana rainforests of Australia world heritage area. Australas Plant Pathol 44:335–348

Seebens H et al (2017) No saturation in the accumulation of alien species worldwide. Nature Comm 8:1–9

Shackleton RT, Le Maitre DC, van Wilgen BW, Richardson DM (2017) Towards a national strategy to optimise the management of a widespread invasive tree (*Prosopis* species; mesquite) in South Africa. Ecosyst Serv 27:242–252

Shackleton RT, Shackleton CM, Kull CA (2019) The role of invasive alien species in shaping local livelihoods and human well-being: a review. J Environ Manage 229:145–157

Shackleton RT, Foxcroft LC, Wood LE, Pyšek P, Richardson DM (1980s) Assessing biological invasions in protected areas: revisiting targeted nature reserves 30 years after the 1980s SCOPE programme. Biol Conserv 243:108424

Strahm W (2008) World Heritage and the IUCN Red List. World Heritage 49:18–29

te Beest M, Howison O, Howison R, Dew LA, Mgobozi Poswa M, Dumalisile L, Van Rensburg SJ, Terblanche C (2017) Successful control of the invasive shrub *Chromolaena odorata* in Hluhluwe-iMfolozi. In: Cromsigt JPG, Archibald S, Owen-Smith N (eds) Savanna ecology and management. Conserving Africa's mega-diversity in the Hluhluwe-iMfolozi Park. Cambridge University Press, Cambridge, pp 336–357

Toral-Granda MV, Causton CE, Jäger H, Trueman M, Izurieta JC, Araujo E, Cruz M, Zander KK, Izurieta A, Garnett ST (2017) Alien species pathways to the Galapagos Islands, Ecuador. PLoS ONE 12:e0184379. https://doi.org/10.1371/journal.pone.0184379

Turner PJ, Downey PO (2010) Ensuring invasive alien plant management delivers biodiversity conservation: insights from an Assessment of *Lantana camara* in Australia. Plant Prot Q 25:102

UNEP-WCMC, IUCN, NGS (2019) Protected planet live report 2019. UNEP-WCMC, IUCN and NGS, Washington

UNESCO (1972) Convention Concerning the Protection of the World Cultural and Natural Heritage. UNESCO, Paris

UNESCO (2017) Operational Guidelines for the implementation of the World Heritage Convention. UNESCO, Paris

Usher MB (1988) Biological invasion of nature reserves: a search for generalisations. Biol Conserv 44:119–135

Van Damme K, Banfield L (2011) Past and present human impacts on the biodiversity of Socotra island (Yemen): implications for future conservation. Zool Middle East 54:31–88

Van Wilgen BW, Wilson JR (eds) (2018) The status of biological invasions and their management in South Africa in 2017. South African National Biodiversity Institute, Kirstenbosch and DST-NRF Centre of Excellence for Invasion Biology, Stellenbosch

van Wilgen BW, Dyer C, Hoffmann JH, Ivey P, Le Maitre DC, Moore JL, Richardson DM, Rouget M, Wannenburgh A, Wilson JRU (2011) National-scale strategic approaches for managing introduced plants: insights from Australian acacias in South Africa. Divers Distrib 17:1060–1075

van Wilgen BW, Fill JM, Baard J, Cheney C, Forsyth AT, Kraaij T (2016) Historical costs and projected future scenarios for the management of invasive alien plants in protected areas in the Cape Floristic Region. Biol Conserv 200:168–177

Veillon R (2014) State of conservation of world heritage properties: a statistical analysis: 1979–2013. UNESCO World Heritage Centre, France

Vilà M, Basnou C, Pyšek P, Josefsson M, Genovesi P, Gollasch S, Nentwig W, Olenin S, Roques A, Roy D, Hulme PE (2010) How well do we understand the impacts of alien species on ecosystem services? A pan-European, cross-taxa assessment. Front Ecol Environ 8:135–144

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of the earth's ecosystems. Science 1997:494–499

Watson JEM, Dudley N, Segan DB, Hockings M (2014) The performance and potential of protected areas. Nature 515:67–73

Wilson JRU, Ivey P, Manyama P, Nanni I (2013) A new national unit for invasive species detection, assessment and eradication planning. S Afr J Sci. https://doi.org/10.1590/sajs.2013/20120111

Wilson JRU, Faulkner KT, Rahlao SJ, Richardson DM, Zengeya TA, van Wilgen BW (2018) Indicators for monitoring biological invasions at a national level. J Appl Ecol 55:2612–2620

Witt ABR, Geertsema H, Giliomee JH (2004) The impact of an invasive ant, *Linepithema humile* (Mayr) (Hymenoptera: Formicidae), on the dispersal of the elaiosome-bearing seeds of six plant species. Afr Entomol 12:223–230

Witt ABR, Kiambi S, Beale T, van Wilgen BW (2017) A preliminary assessment of the extent and potential impacts of alien plant invasions in the Serengeti-Mara ecosystem, East Africa. Koedoe 59:1–16

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Supplementary file 1: Guidelines for applying the proposed monitoring and reporting framework for assessing the status of biological invasions in protected areas

It is important to have holistic and standardised monitoring and reporting frameworks to allow for the provision of meaningful data, comparison between sites, and long-term monitoring of changes in protected areas (PAs) (Figure 1) (Latombe et al. 2017; Shackleton et al. 2020). This is key for guiding adaptive management and policy formulation. This document provides guidelines on how to do this; it focuses on reporting on **current status** (components 1-4), **predictions** (component 5), and the **assessment** (components 6-7).

The first step of the process is to identify the **current status** of biological invasions and their management in the PA (Figure 1). This consists of: (1) evaluating pathways of introduction and spread; (2) compiling an inventory of alien species; (3) identifying current impacts; and (4) reporting on the status of management (cf. van Wilgen and Wilson 2018). Components 1–4 can be conducted concurrently. Following this, **predictions** (5) should be made regarding the threats posed, and the management needs. The final step is **assessment** and includes: (6) identifying the status of knowledge and gaps, and using all the information from components 1-6 to assign an overall threat level (7).

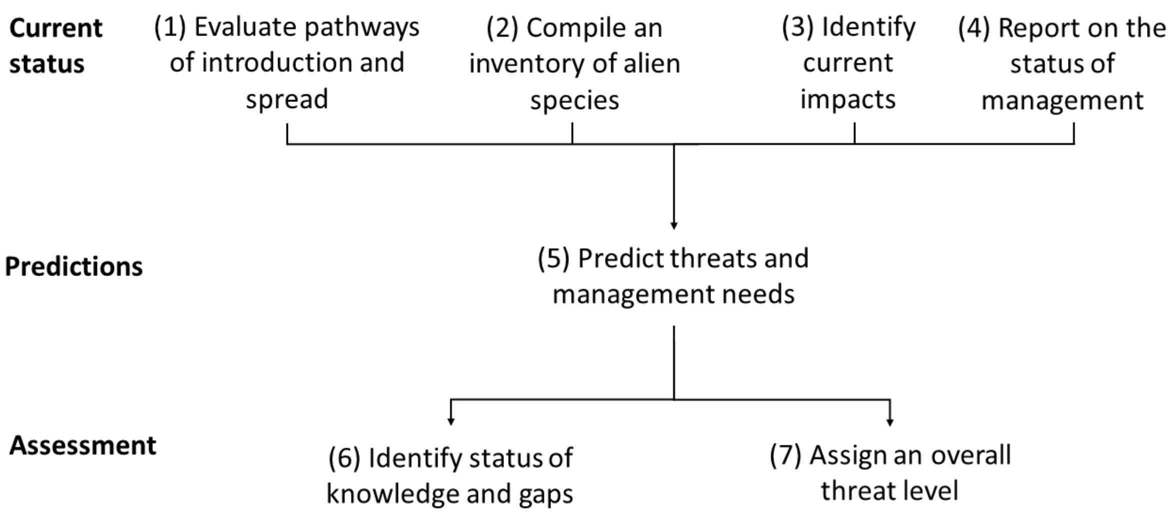

Figure 1: A proposed framework for monitoring and reporting on biological invasions and their management in protected areas globally

A detailed outline of how to apply each component of the framework is given below.

(1) Evaluate pathways of introduction and spread

Understanding pathways (see Box 1; Table 1) is important for determining threats and guiding management. It is therefore crucial to identify the pathways of introduction and spread. This can be done using the six broad categories and 44 sub-categories outlined in the CBD classification scheme (https://www.cbd.int/doc/meetings/sbstta/sbstta-18/official/sbstta-18-09-add1-en.pdf; see Harrower et al. (2017) for guidelines on implementation of the pathway analysis).

Each pathway should be assessed with respect to the likelihood that alien species were introduced along it into the PA in the past, and the extent to which alien species are being introduced along it currently. If possible, a full assessment for each known alien species at the site can be done (e.g. Toral-Granda et al. 2017). If there is a lack of capacity or if data are not available to complete a full species by species pathway assessment, important pathways should be highlighted and discussed (e.g. Wilson et al. 2018) and this information should be supported by examples. Information should also be provided on which pathways are known to be irrelevant or implausible.

Determine whether the pathway is relevant by giving it a risk score of **very high**, **high**, **medium**, **low**, **very low**, **zero, data deficient/unknown,** or **not applicable** (Table 1). If possible, give a description of the threat for each pathway and/or an example of one or more species that was introduced or spread via this pathway. For each relevant pathway, estimate whether introductions and spread through that pathway are **increasing**, **stable**, **decreasing**, or **unknown.**

Table 1: Pathway categories according to the CBD guidelines (Harrower et al. 2017)

CBD Pathway Category for introduction of alien species	**Subcategory**	**Risk**	**Examples /or notes**	**Trends**
(1) Release in nature	Biological control			
	Erosion control/dune stabilization			
	Fishery in the wild (including game fishing)			
	Hunting			
	Landscape/flora/fauna “improvement” in the wild			
	Introduction for conservation purposes or wildlife management			
	Release in nature for use (other than above, e.g. fur, transport, medical use)			
	Other intentional release			
(2) Escape from confinement	Agriculture (biofuel feedstock)			
	Aquiculture/ mariculture			
	Botanical gardens/zoo/aquaria (excluding domestic aquaria)			
	Pet/aquarium/terrarium species (including live food)			
	Farmed animals (including animals left under limited control)			
	Forestry (including reforestation)			
	Fur farms			
	Horticulture			
	Ornamental purposes other than horticulture			
	Research and ex-situ breeding (in facilities)			
	Live food and live bait			
	Other escape form confinement			
(3) Transport-**Contaminant**	Contaminant nursery material			
	Contaminated bait			
	Food contaminant (including of live food)			
	Contaminants on animals (except parasites, species transported by host/vector)			
	Parasites on animals (including species transported by host and vector)			
	Contaminant on plants (except parasites, species transported by host/vector)			
	Parasites on plants (including species transported by host and vector)			
	Seed contaminant			
	Timber trade			
	Transportation of habitat material (soil, vegetation...)			
(4) Transport-**Stowaway**	Angling/fishing equipment			
	Container/bulk			
	Hitchhikers in or on a plane			

	Hitchhikers on ship/boat (excluding ballast water and hull fouling)			
	Machinery/ equipment			
	People and their luggage/equipment (in particular tourism)			
	Organic packing material, in particular wood packaging			
	Ship/boat ballast water			
	Ship/boat hull fouling			
	Vehicles (car, train …)			
	Other means of transport			
(5) **Corridor**	Interconnected waterways/basins/seas Tunnels and land bridges			
(6) **Unaided** by humans	Natural dispersal of IAS across borders that have been introduced through pathways 1–5			

Trends: As an assessor for the site, indicate whether the prevalence and threat of introductions through combined pathways is **increasing**, **stable**, **decreasing**, or **unknown**.

(2) Compile an inventory of alien species

The total known number of alien species at the site must be provided (see Box 1 for definitions of alien and invasive alien species). This number should be broken down into those that are that are simply recorded as alien species and those that are clearly invasive. Numbers of alien species can be reported separately for different taxonomic groups; this will to help assess the sampling effort for different taxa (Latombe et al. 2017; Shackleton et al. 2020). Lists should give the *scientific names* (including authorities) and the taxonomic backbone that was applied (see Essl et al. 2018). If feasible, the approximate date of first recording of each species in the PA should be given. If data are available, and resources permit, data on abundance and distribution should be added and/or discussed.

The list can be compiled using information collected *in situ* (monitoring by managers, rangers, research projects etc.) and/or be determined *ex situ* based on national ((e.g. the South African Plant Invaders Atlas (SAPIA) (Henderson, 2007)) or international databases or literature ((e.g. the Global Biodiversity Information Facility: (GBIF)).

Trends: Report on changes in the number of alien and IAS over time (noting whether changes might be due to changes in sampling intensity and methodology or more introductions). Also, as an assessor, highlight whether the number of listed alien and IAS at the site is **increasing**, **stable**, **decreasing** or **unknown**, between monitoring periods.

(3) Identify current impacts

Discuss the major impacts of IAS at the site (impact is often also referred to as threats – see Box 1). Ideally, this should be done for all listed species, but a list of what the assessor (possibly in consultation with other experts) considers the top 10 or more worst IAS at the site in terms of overall or potential impact can also be done. Specific impacts and impact mechanisms should be mentioned for these species. If possible, for the overall area, determine how many native species are threatened with extinction due to invasions (e.g. using the IUCN's Red List methodology), and how the entire suite of invasions affect major ecosystem processes. This can be guided by GISD (http://www.iucngisd.org/gisd/howto.php).

Information can be based on local site-specific evidence (observed or scientifically studied in the PA) and/or with reference to published work or databases elsewhere in the world, or even drawing on impact-scoring tools such as EICAT (Blackburn et al. 2014), SEICAT (Bacher et al. 2018) and others. Data on EICAT and SEICAT scores will increasingly be available through the IUCN Global Invasive Species Database and could be used to supplement reports (Hawkins et al. 2015).

Trends: As an assessor for the site, indicate whether you believe the overall impacts of IAS to be i**ncreasing**, **decreasing**, **stable**, or **unknown**.

(4) Report on the status of management

Reporting on management should include information on the approaches used, inputs (e.g. financial costs and/or labour indications), outcomes/effectiveness (e.g. eradication, impact reduction, failed control etc.). Use the pointers below to guide data collection and reporting.

Management plan

Discuss whether the PA has management initiatives (if not, state this explicitly) and whether these are informed by a formalised management strategy, plan or guidelines for controlling biological invasions. If the site does have a management plan, discuss when it was first initiated, how often it is updated, and highlight its key components, such as objectives, goals, approaches. Identify the annual budget for management of invasions in the PA.

Prevention, surveillance and detection

Is monitoring of alien species in place in the PA? Are preventative measures such as biosecurity control and pathway management systems in place? If so, discuss these measures. If possible, provide details on annual costs (e.g. budget and/or labour effort).

Eradication

List all species that are recorded as having been eradicated from the site (and give the date when eradication was declared). Do the same for species for which eradication attempts are currently underway, or where an eradication attempts failed. Where possible, also give an indication of costs (e.g. budgets and/or labour effort) and methods used. For failed attempts discuss the reasons for failure, if known.

Containment and impact reduction control measures

Identify measures used for containment and impact reduction of IAS at the site. If possible, provide details on annual input costs (financial inputs and/or labour effort) for managing alien and IAS in the PA as well as control approaches used (physical control, chemical control, cultural control, biological control etc). List IAS that have been contained through management (i.e. those that are no longer spreading and even potentially decreasing) and discuss approaches used listing key examples. List IAS that are still spreading despite ongoing management efforts (give key examples). Also mention any species that are declining due to reasons other than active management.

List any classical biological control agents present at the site, and when they were released and the target IAS. Also assess the success of biological control measures. Use the following guidelines to assess success (adapted from Klein, 2011): (1) successful: no other control measures are needed to reduce the invasive species to acceptable levels in areas where the agents are established; (2) substantial: other methods are needed to reduce the invasive species to acceptable levels, but less effort is required; (3) negligible: in spite of damage inflicted by the agents, control of the invasive species depends on the implementation of other control measures; (4) failed: biological control agents have not established; (5) not determined: either the release of the agents has been too recent to allow for meaningful evaluation, or the programme has not been evaluated.

Challenges and successes

Report any major factors hindering or facilitating management success with regards to overall IAS management.

Overall assessment of management implantation in the protected area

Assess and categorise the overall status of management of biological invasions within the site based on Table 2. List it as: Highly effective, effective, some concern, serious concern, or data deficient.

Table 2 Categorisation of the effectiveness of management within a given protected area. *This table follows the guidelines for IUCN's World Heritage Outlook assessments (see section "Step 3: Assessing protection and management" in IUCN (2012) for more details))

Category	Category description
Highly effective	Successful management is reducing the overall threat and impact of biological invasions and ensures the values and integrity of the site in the long term. There is a guarantee of adequate and sustained funding for management and management implementation
Effective	Management has reduced the threat and impacts of most IAS but more effort is needed to ensure the values and integrity of the site in the long term. Funding for management in the long run is almost certain and adequate
Some concern	Management is taking place but is not effectively reducing the threat and impact of IAS – this could affect the values and integrity of the site in the long term – adaptive management could potentially improve the situation. There is funding but it might not be adequate or sustained in the long run
Serious concern	No management interventions in place, or management interventions are not reducing the threat and impact (spread) of IAS and the values and integrity of the site are in jeopardy in the future. There is no funding for management
Data deficient	No information available

Trends: As an assessor for the site, evaluate whether management response effectiveness is **increasing**, **stable**, **decreasing** or **not applicable** in the site.

(5) Predict threats and management needs

Identify pathways along which alien species might reach the site, and identify alien species that are not currently present within the PA but that have a high probability of being introduced along such pathways (numerous approaches can be used to do this e.g. a watch list as per the methodology of Faulkner et al. 2014, or based on horizon-scanning, climatic models, pathway assessments or expert knowledge). Also discuss the potential for alien species present at the site to become invasive in future, and the potential for current IAS to spread. Finally, discuss how current impacts might change over time. These together represent the site's invasion debt (Rouget et al. 2016).

Highlight key management needs and foci in the future to prevent these threats and continue to manage existing threats.

Trends: As an assessor, evaluate whether threats are **increasing**, **stable**, **decreasing** or **not applicable** in the site. Also assess whether future management is likely to be **capable**, **incapable** or **not applicable** for addressing the threat of biological invasions.

(6) Identify status of knowledge and gaps

Based on the information collated in components 1–5 above, the current knowledge of biological invasions in the site can be determined and tabulated based on the relevant indicators (Table 3).

Table 3 Categorisation of knowledge status and gaps

Indicator	Status of knowledge	Confidence	Notes and recommendations
1. Introduction pathways			
2. Species inventories			
3. Impacts of IAS			
4. Management status			
5. Future threats			

The status of knowledge can be categorised using the following guidelines:

- 1: Pathways: **high** (known for all pathways, taxa, situations); **moderate** (some pathways are known or understood but others are not); **low** (no pathways are known or have been identified but some can be guessed) or **data deficient**. This can provide the basis for identifying knowledge gaps.
- 2: Species inventories: **high** (lists are produced and updated by staff regularly using systematic on-site assessments; all species in the PA are known); **moderate** (on-site monitoring and production of lists is done on an ad hoc and irregular basis; *ex-situ* data are also available); **low** (lists are mainly produced on an *ex situ* basis or no full assessments have been conducted but a few IAS are known) or **data deficient** (no monitoring done or *ex situ* information is available).
- 3: Impacts: **high** (there is research on impacts of IAS within the PA; there is good understanding of impacts of most species); **moderate** (there is some evidence of impacts of some IAS in the PA; impacts for some species present have been researched elsewhere and findings are relevant for the PA); **low** (there is no research on impacts; some evidence can be taken from similar species elsewhere) or **data Deficient** (no relevant information is available).
- 4: Management: **high** (there is good evidence on management inputs and implementation and of the effectiveness of management in the PA i.e. numbers of eradications, changes in species distributions, control costs available, etc); **moderate** (information on management inputs is available and/or management effectiveness can be estimated for species or areas but precise information is lacking); **low** (there is little or no information on management implementation and/or effectiveness but broad trends can be suggested) or **data deficient** (no information is available).
- 5: Future threats: **high** (there is good evidence of future threats backed up by research); **moderate** (future threats are suspected and well known but are not based on any scientific

assessment); **low** (very few future threats are known or acknowledged) or **data deficient** (future threats are unknown).

For each section in Table 3, indicate the level of confidence in the response using a qualitative scale of **high**, **medium** or l**ow** (see Hawkins et al. 2015; Wilson et al. 2018). The type of uncertainty associated with categories should also be listed. These include factors relating to linguistic uncertainty (e.g. different terminologies), epistemic uncertainty (e.g. measurement error, lack of capacity and standardisation), and psychological uncertainty (e.g. issues with subjectivity); see the factors outlined in Latombe et al. (2019). The confidence levels should be based on a combination of the underlying evidence (published reports, physical specimens identified by a taxonomist, field observations, context variation, sampling effort, extrapolations based on reasonable assumptions etc.) and on how recently the evidence was assessed (e.g. an assessment in the last year, decade, or further back).

(7) Assign an overall threat level

The threat level of a site integrates the current and future threats and impacts of biological invasions as well as the capacity and effectiveness of management. Changes to the threat level should trigger management actions and guide decision making for sites.

Categorise the overall threat level as: (**very high threat**, **high threat**, **moderate threat**, **low threat** or **data deficient**). Table 4 provide guidelines for this threat categorisation (considering impacts and threats in the context of corresponding management needs and capacity) from biological invasions to the values and integrity of the PA. This categorisation draws on and adapts existing IUCN and UNESCO guidelines ((see section "Step 2: Assessing threats" in IUCN 2012 for more details; further guidance can be taken form Blackburn et al. (2014); Hawkins et al. (2015)).

Table 4 Categorisation of overall threats. * Note that these categories used for are synonymous with other reporting styles used by the IUCN IAS assessments: (massive – very high), major (high), moderate (low), minimal (very low), data deficient (data deficient).

Very high threat	Invasive alien species have or are likely to induce irreversible changes to community structure and ecosystem services with no likelihood of them returning to their original state resulting in irreversible damage to the values and integrity of the site even with effective management
High threat	Can cause changes to community composition, substantially alter the supply of ecosystem services and thus poses a substantial threat to the values and integrity of the site but can be avoided or reversed with highly effective management
Moderate threat	May cause minor changes in community composition and reduce the supply of some ecosystem services resulting in small-scale (localised) impacts but not fundamentally alter them. These impacts are reversible through management, or impacts will not raise substantially without management and therefore do not post significant threats to the values and integrity of the site
Low threat	May alter individual species fitness but has limited effects on ecosystem services. The threats posed to the values and integrity of the site are very limited. Management could remove these species altogether or absence of management would not raise the threat posed
Data deficient	Insufficient information available on which to base an assessment

Trends: As an assessor, highlight if the future overall threats for the PA are **increasing, decreasing**, **stable** or **unknown**.

Box 1 Glossary of key terms and acronyms used

Alien species (syn. non-native, exotic, non-native) - Alien species are taxa in a given area, whose presence is due to intentional or accidental introduction as a result of human activity (Richardson et al. 2000).

Naturalised - Alien plants that reproduce consistently and sustain populations over several life cycles without direct intervention by humans (or in spite of human intervention); they often recruit offspring freely, usually close to adult plants, and do not necessarily invade or spread widely into natural, seminatural or human-made ecosystems (Richardson et al. 2000).

Invasive alien species (IAS) (syn. Non-native invasive) - Invasive alien species are alien species that have established and spread widely (meaning that they become invasive alien species, IAS); they often have negative impacts on native biodiversity, ecosystem services and/or human well-being (IUCN 2000; Richardson et al. 2011; Jeschke et al. 2014).

Pathway – "Refers to any human mediated means that enables the entry or spread of an alien species within a region or beyond. This includes physical vectors, as well as general activities causing the introduction of alien species." https://www.cbd.int/doc/meetings/sbstta/sbstta-18/official/sbstta-18-09-add1-en.pdf (Harrower et al. 2017).

Threat - The IUCN separates threat into two categories. "**Current** threats refer to activities or occurrences that have an immediately apparent impact affecting a site's values, … while **potential** threats refer to planned activities or evolving trends that could have a future impact if they materialise." (Ospriva et al. 2017).

Environmental Impact Classification of alien taxa (EICAT) – A impact assessment tool for scoring the ecological effects of invasive species, adopted as a tool by the IUCN. https://www.iucn.org/theme/species/our-work/invasive-species/eicat (Hawkins et al. 2015).

World Heritage Sites (WHS) – World Heritage Sites are areas listed under the World Heritage Convention. In this and associated documents use of the abbreviation WHS is always in plural, if a singular site is mentioned it is named in full or as "site".

United Nations Educational, Scientific and Cultural Organisation (UNESCO) – Organisation responsible for implementation of the World Heritage Convention.

International Union for Conservation of Nature (IUCN) – Organisation assisting UNESCO with implementation of the World Heritage Convention as official advisory body on natural heritage.

References

Bacher S et al (2018) Socio-economic impact classification of alien taxa (SEICAT). Methods Ecol Evol 9: 159-168.

Blackburn TM et al. (2014) A unified classification of alien species based on the magnitude of their environmental impacts. PLoS Biol 12: e1001850.

Essl F et al. (2018) Which taxa are alien? Criteria, applications, and uncertainties. BioScience 68: 496-509.

Faulkner KT, Robertson, MP, Rouget M, Wilson JRU (2014) A simple, rapid methodology for developing invasive species watch lists. Biol Conserv 179: 25-32.

Harrower CA, Scalera R, Pagad S, Schönrogge K, Roy, HE (2017) Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission.

Hawkins CL et al. (2015) Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT). Divers Distrib 21: 1360-1363.

Henderson L (2007) Invasive, naturalized and casual alien plants in southern Africa: a summary based on the Southern African Plant Invaders Atlas (SAPIA). Bothalia 37: 215-248.

IUCN (2000) Guidelines for the Prevention of Biodiversity Loss Caused by Alien Invasive Species. Approved by the 51st Meeting of the IUCN Council, Gland Switzerland.

IUCN (2012). IUCN Conservation Outlook Assessments – Guidelines for their applications to natural World Heritage Sites. IUCN.

Jeschke JM et al. (2014) Defining the impact of non-native species. Conserv Biol 28: 1188-1194.

Klein H (2011) A catalogue of the insects, mites and pathogens that have been used or rejected, or are under consideration, for the biological control of invasive alien plants in South Africa. Afr Entomol 19: 515–549.

Latombe G et al. (2017) A vision for global monitoring of biological invasions. Biol Conserv 213: 295-308.

Latombe G, Canavan S, Hirsch H, Hui C, Kumschick S, Nsikani MM, Potgieter LJ, Saul WC, Turner SC, Wilson JRU, Yannelli FA, Richardson DM (2019) A four-component classification of uncertainties in biological invasions: implications for management. Ecosphere 10: e02669.

Osipova E, Shadie P, Zwahlen C, Osti M, Shi Y, Komos C, Bertzky B, Murai M, Van Merm R, Badman T (2017). IUCN World Heritage Outlook 2: A conservation assessment of all natural World Heritage sites. Gland, Switzerland: IUCN.

Richardson DM, Pyšek P, Rejmánek M, Barbour MG, Panetta FD, West CJ (2000). Naturalization and invasion of alien plants: concepts and definitions. Divers Distrib 6: 93-107.

Richardson DM, Pyšek P, Carlton JT (2011) A compendium of essential concepts and terminology in invasion ecology. In: Richardson DM (ed.) Fifty years of invasion ecology. The legacy of Charles Elton, pp. 409-420. Wiley-Blackwell, Oxford.

Rouget M, Robertson MP, Wilson JRU, Hui C, Essl F, Rentería JL, Richardson DM (2016) Invasion debt—quantifying future biological invasions. Diversity and Distributions 22: 445–456.

Shackleton RT, Foxcroft LC, Pyšek P, Wood LE, Richardson DM (2020) Assessing biological invasions in protected areas after 30 years: Revisiting nature reserves targeted by the 1980s SCOPE programme. Biol Conserv 243: 108424.

Toral-Granda MV, Causton CE, Jäger H, Trueman M, Izurieta JC, Araujo E, Cruz M, Zander KK, Izurieta, A, Garnett ST (2017) Alien species pathways to the Galapagos Islands, Ecuador. PLoS ONE 12: e0184379.

van Wilgen BW, Wilson JR (2018) The status of biological invasions and their management in South Africa in 2017. pp. 398. South African National Biodiversity Institute, Kirstenbosch and DST-NRF Centre of Excellence for Invasion Biology, Stellenbosch.

Wilson JRU, Faulkner KT, Rahlao SJ, Richardson DM, Zengeya TA, van Wilgen BW (2018) Indicators for monitoring biological invasions at a national level. J Appl Ecol 55: 2612-2620.

Supplementary file 2: Seven case studies on the threats and management of invasive alien species in seven natural and mixed World Heritage Sites (WHS) based on the proposed monitoring and reporting framework.

1. Aldabra Atoll (Seychelles)

1. Pathways

Pathways of introduction and spread of invasive alien species to Aldabra Atoll WHS are almost exclusively linked to transport stowaways – the unintentional movement of live organisms. The island is uninhabited except for a few park staff, and the main threat is stowaways associated with visitors. Improved biosecurity measures are also likely to have reduced the threat of introducing stowaways. Relevant pathways are explored and detailed in the table below.

CBD Pathway Category	**Subcategory**	**Risk**	**Examples and/or notes**	**Trends**
(1) Release in nature	N/A	Very low	Aldabra is a strict nature reserve and has no resident human population. Only staff employed by the management authority reside there. Release could only be by people travelling to the relatively inaccessible atoll and illegally releasing species.	Stable
(2) Escape from confinement	N/A	Very low	No confined animals or plants kept on Aldabra. Introduced birds on nearby island of Assumption originated from pet birds but these have all been removed. Small possibility of new species being held as pets on Assumption.	Stable
(3) Transport-**Contaminant**	N/A	Very low	Aldabra receives no direct international trade, development assistance or emergency relief.	Stable
(4) Transport–**Stowaway**	Angling/fishing equipment	Low	Fishing is not permitted in the waters around Aldabra, so the atoll receives no fishing vessels, but they do visit nearby islands.	Stable
	Container/bulk machinery/ equipment	Very high	Aldabra receives supplies and equipment via cargo vessels from Mahé which sometimes must beach at the atoll. Comprehensive biosecurity measures have been increasingly taken in the past 7 years on both Mahé and Aldabra, but there remains a high risk of IAS transfer from Mahé. Several potential IAS (introduced plants, unidentified ants and *Achatina* snails) have been detected and eliminated via this pathway.	Decreasing
	Hitchhikers on aeroplanes/ships/ boats and on people and in luggage	Medium	There is no airstrip on Aldabra, so visitors and staff arrive either by vessel from Mahé or by flying to Assumption and then travelling by boat to Aldabra. Extensive biosecurity checks and precautions are now taken (since 2017) including cleaning of clothes and shoes and checking of luggage and any cargo in a dedicated biosecurity building. Tourists arriving by vessel are subject to the same checks above.	Decreasing
	Organic packing material	Low	Rarely used	Stable
	Ship/boat ballast water	Medium	Aldabra receives several large vessels a year. Ballast water is not supposed to be dumped in the nearshore waters, but this is difficult to enforce.	Possibly increasing
	Ship/boat hull fouling	Medium	See above. No cleaning of hulls is required before vessels arrive at Aldabra.	Stable
	Vehicles (cars, trains …)	Zero	There are no vehicles on Aldabra or means of terrestrial transport	Stable
(5) Corridor	N/A	Zero	Aldabra is a remote island in a marine protected area with no permitted development, and no existing waterways, tunnels or land bridges. A proposed airstrip crossing the lagoon in the 1960s	Stable

			received international outcry and resulted in Aldabra's strict protection, so it is highly unlikely this will pose a future risk.	
(6) Unaided	Natural dispersal across borders of IAS that have been introduced through pathways 1–5	Low	Previously a risk as two invasive bird species introduced to the nearby island of Assumption spread naturally by flying unaided to Aldabra once the populations on Assumption were sufficiently high. These risk species have now been eradicated from both islands with little chance of them being re-introduced to Assumption. However, it is possible that other species could be introduced to Assumption and pose a new threat to Aldabra.	Decreasing

Trends: Looking at the combined threat of pathways overall, the threat is **stable** or possibly even decreasing with time.

2. Species inventory

A full list of invasive alien plants, invertebrates and vertebrates present on Aldabra is included in the Aldabra Biosecurity Plan v2.0 (Harper and Cook, 2018). The list includes approximately 70 introduced plant species. Five species are considered to be invasive (*Casuarina equisetifolia, Felis catus*, *Icerya seychellarum*, *Rattus rattus*, and *Stachytarpheta jamaicensis*) with one species considered to be an emerging concern. Only two invasive vertebrates (*R. rattus* and *F. catus*) are now present (other species eradicated – see below). Aldabra appears to have fewer invasive invertebrates than many other islands with four documented species; a scale insect (*I. seychellarum*) potter wasp (*Eumenes maxilllosa*), beetle (*Oryzaephillus surinamensis)*, and a stick-tight flea (*Echidnophaga gallinacea*). Of these five invasive species, only *Casuarina equisetifolia* appears to be increasing, with other species populations remaining stable (with seasonal fluctuations). This knowledge is based on detailed monitoring and assessments compiled over time.

Trends: Overall, due to successful management, the number of invasive species present is **decreasing** with time.

3. Impacts

The top worst invasive species on Aldabra in terms of current or potential impacts are: *C. equisetifolia, F. catus*, *I. seychellarum*, *R. rattus*, and *S. jamaicensis*. *Rattus rattus* and *F. catus* both pose a serious threat to many endemic and native species through predation (Harper et al. 2015; Harper and Bunbury, 2015). *Rattus rattus* and *F. catus* have also caused numerous extinctions of native species on islands around the globe and are a major concern (Clavero and García-Berthou, 2005). There is also concern that the presence of *R. rattus* could be having indirect impacts on the marine ecosystem of Aldabra via direct effects on seabirds and guano reduction. *Casuarina equisetifolia* is likely to be a future problem through displacement of native biota and alteration to ecosystem properties and is an issue in other parts of the world (see review by Potgieter et al. 2014). All other species are considered to have minimal impacts currently but have the potential to become problems. For example, *Stachytarpheta jamaicensis* is known to have allelopathic properties (Kuo, 2001).

Trends: The overall impacts of invasive species at Aldabra are considered to be **stable** or slightly decreasing. This is attributable to good biosecurity and control of high-impact species. The recent eradications (see next section) have removed several key IAS threats, and biosecurity measures have been substantially strengthened since 2015, considerably reducing the threat posed by new invasive species.

4. Management

Management has taken place in Aldabra since the 1980s but has been sporadic. However, management has been more consistent in the last decade, with management activities falling under the site's management plan, which was last updated in 2016. Management of most IAS on Aldabra Atoll and on nearby Assumption Island has been successful.

Good biosecurity measures and infrastructure are now in place for Aldabra and very few people visit and live on the atoll, so the probability of future introductions is relatively low. Aldabra has an effective biosecurity system supported by excellent programmes for the continued management of IAS. For example, all equipment, staff and luggage are checked before leaving Mahé to go to Aldabra. Most checked items are in sealed plastic barrels and supply vessels are also checked before leaving port. Rat trapping and invertebrate control is carried out in transit. All supplies and people are again checked on Aldabra by designated biosecurity officers in a dedicated biosecurity building. All people transported to the island are briefed on the importance of good biosecurity practices. IAS management and emergency protocols, including surveillance and action plans for a range of invasive species incursions, are integrated into the Aldabra Management Plan and biosecurity plan.

There have been a number of successful eradications on Aldabra. *Capra hircus* were eradicated in 2012 (using the Judas goat method, at a cost of US$ 185,105; Bunbury et al. 2018) after 25 years of intermittent eradication efforts; *Pycnonotus jocosus* was declared eradicated from Aldabra in 2013 (by mist-netting; Bunbury et al. 2013) and from Assumption in 2016 (by mist-netting and shooting; Bunbury et al. 2019). *Foudia madagascariensis* was declared eradicated from Aldabra in 2017, and from Assumption in the same year (by mist-netting and shooting; Bunbury et al. 2019); *Agave sisalana* was confirmed eradicated from Aldabra in 2019 (using targeted herbicide application methods described in van Dinther et al. (2015), after 40 years of sporadic control efforts (Bunbury and van Dinther, 2019). At least 12 species are no longer present although exact details are not available on their disappearance.

Two plant species (*Casuarina equisetifolia* and *Stachytarpheta jamaicensis*) are being considered for control. Additionally, *F. catus* and *R. rattus* are being strongly considered for eradication from Aldabra in the next few years and would substantially reduce threats if managed (Russell and Holms, 2015; Jones et al 2016). Research on their movements and ecology, and bait trials were undertaken in 2013–2014 (Harper et al. 2015; Harper and Bunbury 2015).

Biological control has also been used on Aldabra. The coccid *Icerya seychellarum* was successfully reduced by the biological control agent *Rodolia chermesina* which was introduced in the 1980s, after which coccid numbers were reduced to much lower levels. Periodic monitoring has not decteced any increase the coccids in abundance (Seychelles Island Foundation, unpublished data).

Assessment: Based on the available evidence it is suggested that overall management of all IAS within Aldabra is categorised as substantial/**effective**. Highly effective management responses are in place and management has reduced the threat and impacts of most IAS. However, more effort is needed to ensure the values and integrity of the site in the long-term.

Trends: Response effectiveness has been **increasing** over time.

5. Predictions on future threats/needs

A number of invasive species not currently present on Aldabra may pose future threats through accidental introductions from nearby islands via boat transport, such as *Anoplolepis gracilipes*, *Technomyrmex albipes*, *Mus musculus*, *Rattus norvegicus*, *Achatina* sp. and *Aleurodicus disperses*. The invasive marine algae *Caulerpa bikinensis* also might pose a potential threat as it is invasive around nearby islands. A full list of potential IAS with distribution, pathway assessment, and threat analysis is provided in the Aldabra Biosecurity Plan (2018). One serious existing threat worth noting is *F. catus,* which is currently restricted to Aldabra's largest island of Grande Terre, but its (natural) spread to other islands (via swimming or being carried by currents across channels of varying width) would be catastrophic for Aldabra rails, seabirds, land birds and small reptiles.

The most urgent management need for IAS, in addition to continued stringent biosecurity measures, is eradication of rats and cats; this would bring enormous benefits to Aldabra's terrestrial and probably biodiversity. Future threats from IAS at Aldabra (besides *Felis catus*) are decreasing with the recent tightening of biosecurity measures. Given the success of recent invasive species control, including several eradications, future management needs for any new biological invasions are likely to be addressed.

Trends: The future threats remain **stable** and the site is **capable** of dealing with them.

6. Knowledge status and gaps

Indicator	**Status of knowledge**	**Confidence**	**Notes and recommendations**
1. Introduction pathways	High	High	With limited pathways, the knowledge of threats from all pathways is well known and potentially invasive taxa have been identified and their distribution and pathway analysis detailed (Aldabra biosecurity protocol v2.0, 2018)
2. Species inventories	Moderate	High	On-site monitoring and production of inventories has been done recently. Comprehensive plant and vertebrate inventories now exist but the status of several plant species is unknown and there is a lack of knowledge of the status of invertebrates at Aldabra.
3. Impacts of IAS	Moderate	High	Published research on impacts of rats and introduced birds (prior to their eradication) from Aldabra and some understanding of IAS impacts from routine monitoring programmes. However, impacts are not known for all species and for several, e.g. *C. equisetifolia* and *F. catus* impacts are assumed from relevant findings elsewhere and the precautionary approach is taken in their management.
4. Management status	High	High	There is effective management of IAS threats on Aldabra, including several recent successful eradications (including some, such as feral goats and sisal, which were completed after decades of work, with others, such as the introduced birds, in response to new incursions). Considerable effort is made to publish and disseminate information on the lessons learned from IAS management and research on Aldabra, including results of trials and cost information.
5. Future threats	High	High	Good evidence of potential future threats included in the biosecurity plan, backed up by research and mitigation strategies in place.

7. Overall assessment

The overall threat level from IAS to the values and integrity of Aldabra Atoll is assessed as **High threat** and is backed by good evidence. Several key IAS have been eradicated in the past five years, which shows effective management but the substantial threat posed by rats and cats to the native biodiversity of Aldabra remains and will continue to seriously affect community composition, habitat connectivity, ecosystem processes and functions, and threatened species persistence and recovery. *Rattus rattus* and *F. catus* populations are likely to be relatively stable, having reached peak numbers long ago, but their presence is an ongoing threat to the values and integrity of Aldabra, making eradication programmes essential for reducing threats.

Trends: The overall threats for Aldabra are **decreasing** (e.g. threats from feral goats, invasive alien birds and sisal removed, biosecurity measures strengthened; most threatening IAS on Aldabra are not increasing in abundance or range).

References

Bunbury N, von Brandis R, Currie J, Jean-Baptiste M, Accouche W, Souyave J, Haupt P, Fleischer-Dogley F (2013) Goats eradicated from Aldabra Atoll. Aliens: The Invasive Species Bulletin, 33: 18-22.

Bunbury N, Haverson P et al. (2019) Five eradications, three species, three islands: overview, insights and recommendations from invasive bird eradications in the Seychelles. In Veitch CR, Clout MN, Martin AR, Russell JC, West CJ (Eds.). Island invasives: Scaling up to meet the challenge. Proceedings of the international conference on island invasives 2017. Occasional Paper SSC no. 62. Gland, Switzerland: IUCN. xiv + 734pp.

Bunbury N, Mahoune T, Raguain J, Richards H, Fleischer-Dogley F (2013) Red-whiskered bulbul eradicated from Aldabra. Aliens 33: 7-8.

Bunbury N, van Dinther M (2019) Sisal on Aldabra: Success after 40 years of eradication attempts. Kapisen, Newsletter of the Plant Conservation Action Group (Seychelles) 22: 13–15

Bunbury N, von Brandis R, Currie JC, van de Crommenacker, J, Accouche W, Birch D, Chong-Seng L, Doak N, Haupt P, Haverson P, Jean-Baptiste M, Fleischer-Dogley F (2018) Late stage dynamics of a successful feral goat eradication from the UNESCO World Heritage site of Aldabra Atoll, Seychelles. Biol Invasions 20: 1735-1747.

Clavero M, García-Berthou E (2005) Invasive species are a leading cause of animal extinctions. Trends Ecol Evol *20*: 110.

Harper GA, Bunbury N (2015) Invasive rats on tropical islands: their population biology and impacts on native species. Glob Ecol Conserv 3: 607-627.

Harper GA, van Dinther M, Russell JC, Bunbury N (2015) The response of black rats (*Rattus rattus*) to evergreen and seasonally arid habitats: informing eradication planning on a tropical island. Biol Conserv 185: 66-74.

Harper GA, Cook L (2019) Aldabra Atoll Biosecurity Plan v2.0. Seychelles Islands Foundation, Republic of Seychelles.

Jones HP et al. (2016) Invasive mammal eradication on islands results in substantial conservation gains. Proc Nat Acad Sci USA 113: 4033-4038.

Kuo YL (2001) Autecological characteristics and allelopathic potential of the invasive species *Stachytarpheta jamaicensis*. Taiwan J For Sci 16: 103-14.

Potgieter LJ, Richardson DM, Wilson JR (2014) *Casuarina:* biogeography and ecology of an important tree genus in a changing world. Biol Invasions 16: 609-633.

Russell JC, Holmes ND (2015) Tropical island conservation: rat eradication for species recovery. Biol Conserv 185: 1-7.

van Dinther M, Bunbury N, Kaiser-Bunbury CN (2015) Trial of herbicide control methods for sisal *Agave sisalana* in the arid island environment of Aldabra Atoll, Seychelles. Conserv Evidence 12: 14-18.

2. Doñana National Park (Spain)

1. Pathways

Although pathways relating to purposeful introductions are likely to be low risk, there is still concern that potential introductions will occur from pathways relating to transport contaminants, stowaways and unaided by humans though natural dispersal over time. This assessment is a very basic overview for the site and detailed assessments for each listed species are still needed.

CBD Pathway Category	Subcategory	Risk	Examples and/or notes	Trends
(1) Release in nature	Biological control	Very Low	Biological control initiatives are increasing slowly in the broader region including in Portugal and there is potential relevance for this pathway in the future. The protected status of the site will likely prevent any future purposeful introductions through other subcategories of this pathway.	Stable
(2) Escape from confinement	Agriculture, Aquaculture, Pets, Forestry, horticulture	High	This pathway is likely to be one of the most prominent for the site. Aquaculture species have escaped and spread into the PA (e.g. *Procambarus clarkii* – Oficialdegui et al. 2020). There are many residential and agricultural areas around the park and so escape from agriculture, pets, forestry and horticulture are likely. For example, domestic and feral dogs and cats (*Canis lupus familiaris* and *Felis catus*) enter the site regularly and this pathway is also relevant for *Oxyura jamaicensis. Acacais, and Eucalypts* are escapees of forestry and *Carpobrotus edulis* commonly escapes gardens.	Increasing
(3) Transport-**Contaminant**	Seed contaminant, Transportation of habitat material	Moderate	Some species might enter as contaminants. It is highly suspected that *Oxalis pes-caprae* was introduced as a contaminant during native tree reforestation initiatives in Doñana. Introduction as a transport contaminant could possibly be relevant for *Arctotheca calendula, Xanthium strumarium.*	Unknown
(4) Transport–**Stowaway**	Containers/bulk, hitchhikers on ship/boat, machinery and equipment, people and their luggage, boat fouling, vehicles	Very high	*Arctotheca calendula* and *Xanthium strumarium* were most likely introduced and spread as stowaways on vehicles, equipment or people. Similarly, many of the fish species, aquatic invertebrates and aquatic invasive plants may have been introduced and spread as hitchhikers on boats.	Increasing
(5) Corridor	N/A	Zero	This is not relevant	Stable
(6) Unaided	Natural dispersal across borders of IAS that have been introduced through pathways 1–5	Very high	This is a key pathway and likely for species such as *Carpobrotus edulis, Opuntia* spp. and all listed bird species as well as other plant and fish species (Gassó et al. 2012; Sanz-Aguilar et al. 2014).	Increasing

Trends: Overall the change in pathway threats for the areas are **unknown** but are likely stable, as a few biosecurity or preventative measures are in place and purposeful introductions are unlikely.

2. Species inventory

It is suspected that there are 75 IAS in the Doñana WHS, although there could be more. This includes 33 plant species, 19 fish, seven birds, five freshwater and marine invertebrates, three insects, four micro-organisms, three mammals and one reptile species (Díaz-Paniagua et al. 2002; Fernández-Delgado et al. 2000; Frisch et al. 2006; Groom et al. 2006; Garcia-Murillo et al. 2007; De Vita et al.

2012; Gassó et al. 2012; De Vita et al. 2013; Sanz-Aguilar et al. 2014; Florencio et al. 2015; Céspedes et al. 2017 and 2019; Doñana Annual Reports 2010-2015). This list is based on a literature survey (with some partial in situ assessments as well as ex situ information) and expert consultation (e.g. pers. comm. with G. Janess and R. Fernández-Zamudio).

Trends: Trends cannot be accurately assessed over time (**unknown**) due to data deficiency. However, it is suspected that the number of species listed is stable or might be increasing slightly over time.

3. Impacts

Plants with severe negative impacts on biodiversity and ecosystem services include the tree species *Acacia melanoxylon* and *Eucalyptus camaldulensis*, the water weed *Azolla filiculoides*, the succulents *Carpobrotus edulis*, and *Opuntia* spp. and the herbs *Arctotheca calendula* and *Xanthium strumarium*. *Eucalyptus camaldulensis* and *A. melanoxylon* reduce native species richness, consume large amounts of water, and alter fire regimes (Le Maitre et al. 2011). *Carpobrotus edulis* alters dune formation and soil chemistry, displaces native plants (Novoa et al. 2013; Campoy et al. 2018) and affects the diversity of native invertebrate assemblages (Rodríguez et al. 2020). Like other invasive floating aquatic plants, *A. filiculoides* alters water chemistry and flow, negatively affects native species diversity and the utility of water bodies for humans (Fernández-Zamudio et al. 2010 and 2013; Keller et al. 2018; Rodríguez-Merino et al. 2020). The invasive plant *X. strumarium* is toxic to animals, allelopathic and has negative effects on native plant diversity (Akhtar et al. 2014; Seifu et al. 2017). *A. calendul*a is also toxic to mammals. The invertebrates *Eriocheir sinensis, Procambarus clarkii* and *Trichocorixa verticalis* have major negative impacts on native biodiversity and ecosystem function (Groom et al. 2006; Coccia et al. 2016). The invasive fish, *Cyprinus carpio* and *Carassius auratus* impact water quality (increase turbidity), and *Ameiurus melas, Gambusia holbrooki, Fundulas heteroclitus* and *Micropterus salmoides* predate on native fauna (Elvira and Almodovar, 2001; Carol et al. 2006). In Doñana, invasive *G. holbooki* are known to affect the egg-laying behaviour of the Spanish pigmy newt (*Tritrus* pygmaeus) (Cabrera-Guzmán et al. 2019). *Linepithema humile* is known to displace other insect species and has negative impacts on plant seed banks (Carpentero et al. 2007; Angulo et al. 2011; Blight et al. 2017). Invasive mammals such as *Felis catus* predate on native animal species and can impact their richness and diversity (Fernández-Aguilar et al. 2012). The invasive bird *Oxyura jamaicensis* hybridizes with native waterfowl and poses a major threat to the threatened species (*Oxyurga leucocephalai*) (Muñoz-Fuentes et al. 2007. The invasive pathogens *Phytophthora cinnamomi* and *Pythium spiculum* are of concern for native tree heath (De Vita et al 2012 and 2013; González et al. 2017).

Trends: Trends relating to impact are **unknown** as no long-term studies in the WHS have been conducted. However, it is thought that impacts are likely to be stable or increasing.

4. Management

Although detailed information on management in the peer reviewed academic literature is sparse, annual reports of the national park contain good information on IAS management (Doñana Annual Research Reports 2000-2016 and Annual Reports of Monitoring Programs 2003-2015). Almost all IAS are under some form of management guided by broad scale management plans.

Doñana conducts regular monitoring for many invasive species (e.g. *click the link for an example relating to C. sapidus*).There have been two successful plant eradications (*Melia azedarach* and

Abutilon theophrasti). Attempts to eradicate other plant species remain ongoing, and many show good progress, for example, management of *O. pes-caprae,* which also involves participation by volunteers (e.g. *click the link for an example relating to O. pes-caprae*). There has also been successful control of several invasive animals. There is an early detection and rapid response system in place for invasive mammals (*Canis lupus familiaris*, *Felis catus,* and *Procyon lotor*). *Trachemys scripta* may have been eradicated but further monitoring is needed to confirm this. Attempts are also underway to eradicate the invasive fish *Ameiurus melas*.

Widespread plant species *E. camaldulensis*, *A. filiculoides, C. edulis* and *Xanthium strumarium* have been manually controlled though cutting for many years, but progress has been slow. *Azolla filiculoides* was initially managed through manual control during the early stages of invasion, but efforts have not had long-term continuity due to difficulty in removing the plant and poor long-term results. Some micro-organisms have undergone experimental control trials in Doñana to help inform future management (González et al. 2017). The WHS also has a strong volunteer programme to help with control. Gutiérrez-Yurrita et al. (2016) proposed to promote utilisation of *P. clarkii* to reduce impacts and improve management, but this approach is controversial.

Assessment: Management success could be categorised as partial with **some concern**, as good systems are in place, but more time and effort are needed.

Trends: Reports from 2010-2015 seem to indicate that management efforts are **increasing** slightly over time.

5. Predictions on future threats/needs

There are early detection programs for some species considered to be a future threat, such as for *Canis lupus familiaris*, *Felis catus,* and *Procyon lotor*. The species distribution models produced by Gasso et al. (2012) and Rodríguez-Merino et al. (2019) indicate certain plant species could be of future concern and should be monitored. Management is likely to be able to address these issues if identified early as there is the capacity to do so.

Certain species are still causing major current impacts despite management, including; *P. clarkii and C. edulis* and *E. camaldulensis.* Attempts for other species have been abandoned. For species causing management difficulty (e.g. *Azolla filiculoides*) the consideration of novel approaches to management, such as biological control, might be needed (McConnachieet al. 2003). A detailed pathway analysis would be useful for the site. Building on currently ongoing citizen control initiatives could also help improve control in the long-term.

Trends: It is suspected that threats to the site are **increasing** but the site should be **capable** of dealing with them.

6. Knowledge status and gaps

Indicator	Status of knowledge	Confidence	Notes and recommendations
1. Introduction pathway	Low	Low	Pathways for each species have not specifically been assessed, but many can be inferred, and a detailed analysis is still needed.
2. Species inventories	Moderate	Low	Currently in-depth assessment and full species lists are not easily available, however, a lot of information is available in the literature and for specific species there are annual reports for the site.
3. Impacts of IAS	Moderate	Moderate	There is work on impacts taking place within the WHS and there is also relevant global literature to draw on for many of the species.
4. Management status	High	High	Annual park management reports outline the management of IAS very well and good attempts to control IAS are in place.
5. Future threats	High	Moderate	Threats have been identified and early detection programs are in place, there are also distribution models available for plants in Spain, which could highlight threats in the future.

7. Overall assessment

Based on the assessments it can be concluded that the threat of IAS to the Doñana WHS is **High** (the WHS was previously categorised as data deficient). In general, there is evidence of the occurrence of high impact invasive species although there is some uncertainty in the data in some places, especially for pathways. There is evidence of good attempts to manage IAS at the site, although threat from many IAS remains high.

Trends: The overall trend seems to be **stable** although this conclusion is not backed up by robust data and longer-term monitoring is needed.

References

Akhtar S, Bangash N, Asghar R, Munir M, Khalid N (2014) Allelopathic assessment of selected invasive species of Pakistan. Paki J Bot 46: 1709-1713.

Angulo E, Caut S, Cerda X (2011) Scavenging in Mediterranean ecosystems: effect of the invasive Argentine ant. Biol Invasions 13: 1183-1194.

Blight, O, Josens R, Bertelsmeier C, Abril S, Boulay R, Cerda X (2017) Differences in behavioural traits among native and introduced colonies of an invasive ant. Biol Invasions 19: 1389-1398.

Cabrera-Guzmán E, Díaz-Paniagua C Gomez-Mestre I (2019) Invasive mosquitofish (*Gambusia holbrooki*) affect egg-laying and behaviour of Spanish pygmy newts (*Triturus pygmaeus*). Amphib-Reptil, 40: 103-112.

Campoy JG, Acosta AT, Affre L, Barreiro R, Brundu G, Buisson E, González L, Lema M, Novoa A, Retuerto R, Roiloa SR (2018) Monographs of invasive plants in Europe: *Carpobrotus*. Bot Lett 165: 440-475.

Carpintero S, Retana J, Cerdá X, Reyes J, Arias de Reyna L (2007) Exploitative strategies of the invasive Argentine ant (*Linepithema humile*) and native ant species in a Southern Spanish pine forest. Environ Entomol 36: 1100-1111.

Carol J, Benejam L, Alcaraz C, Vila-Gispert A, Zamora L, Navarro E, Armengol J, García-Berthou, E (2006) The effects of limnological features on fish assemblages of 14 Spanish reservoirs. Ecol Freshw Fish 15: 66-77.

Céspedes V, Coccia C, Carbonell JA, Sánchez MI, Green AJ (2019) The life cycle of the alien boatman *Trichocorixa verticalis* (Hemiptera, Corixidae) in saline and hypersaline wetlands of south-west Spain. Hydrobiologia, 827: 309-324.

Coccia C, Fry B, Ramirez F, Boyero L, Bunn SE, Diz-Salgado C, Walton M, Le Vay L, Green AJ (2016) Niche partitioning between invasive and native corixids (Hemiptera, Corixidae) in south-west Spain. Aquat Sci 78: 779-791.

De Vita P, Serrano MS, Callier P, Ramo C, García LV, Sánchez Hernández ME (2012). Phytophthora root disease: a new threat for cork oaks at Doñana National Park (south-western Spain). IOBC/wprs Bulletin 76: 93.

De VitaP, Serrano MS, Ramo, C, Aponte C, Garcia LV, Belbahri, L, Sanchez ME (2013) First Report of Root Rot Caused by *Pythium spiculum* Affecting Cork Oaks at Doñana Biological Reserve in Spain. Plant Disease 97: 991-991.

Elvira B, Almodóvar A (2001) Freshwater fish introductions in Spain: facts and figures at the beginning of the 21st century. J Fish Biol 59: 323-331.

Fernández-Aguilar X, Molina-Vacas G, Ramiro V, Carro FA, Barasosa JÁ, Vicente J, Gutiérrez C (2012) Presence of raccoon (*Procyon lotor*) in Doñana National Park and its surroundings. Galemys 24: 76-79.

Fernández-Zamudio, R., García-Murillo, Cirujano (2010) Germination characteristics and sporeling success of *Azolla filiculoides* Lamarck, an aquatic invasive fern, in a Mediterranean temporary wetland. Aquat. Biol 93: 89-92.

Fernández-Zamudio R, Cirujano S, Sánchez-Carillio S, Meco A, García-Murillo P (2013) Clonal reproduction of *Azolla filiculoides* Lam.: Implications for invasiveness. Limnetica, 32: 245-252.

Florencio M, Fernández-Zamudio R, Bilton DT, Díaz-Paniagua C (2015) The exotic weevil *Stenopelmus rufinasus* Gyllenhal, 1835 (Coleoptera: Curculionidae) across a “host-free” pond network. Limnetica, 34: 79-84.

Frisch D, Rodríguez-Pérez H, Green AJ (2006) Invasion of artificial ponds in Doñana Natural Park, southwest Spain, by an exotic estuarine copepod. Aquat Conserv: Marine Freshw Ecosyst 16: 483-492.

García Murillo P, Fernández Zamudio MDR, Cirujano Bracamonte S, Sousa Martín A, Espinar JM (2007) The invasion of Doñana National Park (SW Spain) by the mosquito fern (*Azolla filiculoides* Lam). Limnetica 26: 43-250.

Gassó N, Thuiller W, Pino J, Vilà M (2012) Potential distribution range of invasive plant species in Spain. NeoBiota 12: 25-40.

Groom MJ, Meffe GK, Carroll CR (2006) Principals of Conservation Biology. Sinauer Associates, Sunderland, MA.

Gonzáles M, Romero MA, Ramo C, Serrano MS, Sánchez ME (2017) Control of *Phytophthora* root rot on Mediteranean *Quercus* spp. using fosetyl-Al trunk injections. Phytopathol Mediterr 56: 340.

Gutiérrez-Yurrita PJM, Martin-Garcia L, Montes C (2016) Ecological design of a crayfishing program to control population density of the invasive species *Procambarus clarkii* in Doñana National Park freshwater marsh (Spain). Appl Ecol Environ Res 13: 513-533.

Josens R, Bertelsmeier C, Abril S, Boulay R, Cerda X (2017) Differences in behavioural traits among native and introduced colonies of an invasive ant. Biol Invasions 19: 1389-1398.

Keller RP, Masoodi A, Shackleton RT (2018) The impact of invasive aquatic plants on ecosystem services and human well-being in Wular Lake, India. Reg Environ Change18: 847-857.

Le Maitre DC, Gaertner M, Marchante E, Ens EJ, Holmes PM, Pauchard A, O'Farrell PJ, Rogers AM, Blanchard R, Blignaut J, Richardson DM (2011) Impacts of invasive Australian acacias: implications for management and restoration. Divers Distrib 17: 1015-1029.

Oficialdegui FJ, Delibes-Mateos M, Green AJ, Sánchez MI, Boyero L, Clavero M (2020) Rigid laws and invasive species management. Conserv Biol DIO:10/1111/coi.13481.

McConnachie AJ, De Wit MP, Hill MP, Byrne MJ (2003) Economic evaluation of the successful biological control of *Azolla filiculoides* in South Africa. Biol Control 28: 25-32.

Muñoz-Fuentes V, Vilà C, Green AJ, Negro JJ, Sorenson MD (2007) Hybridization between white-headed ducks and introduced ruddy ducks in Spain. Mol Ecol 16: 629-638.

Novoa A, González L, Moravcová L, Pyšek P (2013) Constraints to native plant species establishment in coastal dune communities invaded by *Carpobrotus edulis*: implications for restoration. Biol Conserv 164: 1-9.

Rodríguez J, Novoa A, Cordero-Rivera A, Richardson DM, González L (2020) Biogeographical comparison of terrestrial invertebrates and trophic feeding guilds in the native and invasive ranges of Carpobrotus edulis. NeoBiota 56: 49-72.

Rodríguez -Merino A, García-Murillo P, Cirujano S, Fernández-Zamudio R (2018) Predicting the risk of aquatic plant invasions in Europe: How climatic factors and anthropogenic activity influence potential species distributions. J Nature Conserv 45: 58-71.

Rodríguez-Merino A, Fernández-Zamudio R, García-Murillo P, Muñoz J (2020) Climatic niche shift during *Azolla filiculoides* invasion and its potential distribution under future scenarios. Plants 8: 424.

Sanz-Aguilar A, Anadón JD, Edelaar P, Carrete M, Tella JL (2014) Can establishment success be determined through demographic parameters? A case study on five introduced bird species. PLoS ONE 9: 110019.

Seifu A, Merawi E, Ayenew A, Faris G, Seboka N, Misganaw M, Bekele T (2017) Impact of invasive alien plant *Xanthium strumarium* on species diversity and composition of invaded plant communities in Borena zone Ethiopia. Biodiv Int J 1: 15-22.

3. Galapagos Islands (Ecuador)

Assessment completed by the Charles Darwin Foundation and the Galápagos National Park Directorate, in collaboration with the Galapagos Biosecurity Agency

1. Pathways

Pathways of introduction and spread of alien species in the Galapagos Islands fall under at least seven pathway categories and 25 subcategories (Table 1). Unless otherwise indicated, all information on pathways was taken from Toral-Granda et al. (2017), which uses the CBD 2014 categories, with minor adaptations to better fit the situation in Galapagos. The risk of these pathways bringing new species with long-lasting effects on the biodiversity and ecosystems in the Galapagos Islands is assessed from very low to very high threat. Categories and subcategories that are listed as very high risk are those pathways that are: 1) important historically, 2) are associated with a high number of species that are currently known to be invasive or have high potential to become invasive and 3) continue to be used on a regular basis (evidence from new species introductions or interceptions by biosecurity officers).

Of the established species, almost half were introduced intentionally and 74% of these are plant species. Consequently, most species that were introduced unintentionally arrived on plants and plant associated material (Toral-Granda et al. 2017).

CBD Pathway Category for introduction of IAS	Subcategory	Risk	Examples for Galapagos and/or notes	Trends
(1) Release in nature	Biological control	Very low (if protocols for biocontrol programs are followed)	Only one tested host specific species has been introduced for biological control; the vedalia beetle *Rodolia cardinalis,* to control the invasive cottony cushion scale *Icerya purchasi* (Calderón Alvarez et al. 2012, Hoddle et al. 2013). Biological control is now being considered for managing other invasive species (*Philornis downsi, Rubus niveus* and *Solenopsis geminata*).	Increasing
	Fishery in the wild (including game fishing)	Very low	Two fish species have been introduced to Galapagos. Tilapia (*Oreochromis niloticus*) was first recorded in the only freshwater lake in Galapagos (San Cristóbal island) in 2006 and eradicated in 2010 (Phillips et al. 2012). Pacific fat sleeper *Dormitator latifrons* was recorded in 1992 - its status is unknown (Phillips et al. 2012).	Decreasing
	Hunting	Medium	*Capra hircus,* was first recorded in 1685, and was introduced to many islands by whalers or pirates so they could be hunted on subsequent trips (Heyerdahl and Skolsvod 1956). After successful eradication from Marchena Island, goats were re-introduced to the island for hunting (Campbell et al. 2004) and are now also reported on other uninhabited islands where they were previously eithr not registered or had been eradicated.	Decreasing
	Release in nature for use (other than above, e.g. fur, transport, medical use)	Low	The smooth-billed ani *Crotophaga ani* was first recorded in 1962 and was probably introduced to control ticks on cattle (Phillips et al. 2012).	Unknown
	Other intentional release	Low	Mangrove crab *Cardisoma craissum* was released intentionally in 1973 (Hickman and Zimmerman 2000).	Unknown
(2) Escape from confinement	Agriculture and horticulture (including biofuel feedstock)	Very high	At least 687 plant species have been introduced for agricultural and horticultural purposes. Of these, 145 are naturalized and found in the Galapagos National Park. Invasive species introduced for agricultural use include: *Cedrela odorata*, *Cinchona pubescens*,	Increasing

			Melinis minutiflora, *Passiflora edulis*, *Persea americana*, *Pennisetum purpureum*, *Psidium guajava*, *Rubus niveus*, *Syzygium jambos* and many more (Rentería et al. 2012, Gardener et al. 2013, Jäger 2015, Rivas-Torres et al. 2018). The same is true for some of those introduced as ornamentals, like *Bryophyllum pinnatum*, *Cordia alliodora*, *Furcraea hexapetala*, *Lantana camara*, *Leucaena leucocephala*, *Tradescantia fluminensis* and many more (Gardener et al. 2013). Many of these species have the potential to become invasive in the future; hence the numbers might increase (Gardener et al. 2013). With an increasing number of residents in Galapagos and a high number of prohibited fruits, plants and seeds intercepted by biosecurity inspectors (Toral-Granda et al. 2017), and an unknown rate of undetected introductions, the risk for this pathway is very high.	
	Pet/aquarium/terrarium species	Low to Medium	In total, 11 vertebrate species had been introduced as pets but most of them vanished shortly after, for example, unidentified species of monkeys, a cotton-top tamarin and an ocelot (Phillips et al. 2012). However, some of these, like *Felis catus* and *Canis lupus familiaris* have become invasive (Phillips et al. 2012). *Felis catus* was first introduced in 1832 and both domestic and feral populations are common. So far, they have only been eradicated from Baltra Island - in 2004 (Jiménez-Uzcátegui et al. 2007). *Canis lupus familiaris* was first recorded in 1685 (Heyerdahl and Skolsvod 1956) and feral populations can be found on Santa Cruz and San Cristóbal (Jiménez-Uzcátegui et al. 2007). In the past, pedigree dogs and other prohibited animals have illegally been brought to Galapagos and interception data by the biosecurity agency shows that attempts are still made to bring animals to the islands (Toral-Granda et al. 2017). With a strengthened biosecurity agency, the risk should go down from medium to low.	Stable
	Farmed animals (including animals left under limited control)	Low	Sixteen vertebrate species and one invertebrate species (the giant African snail *Lissachatina fulica*) have been introduced for farming. Ten of these are considered invasive in Galapagos. Most of these were introduced by the first settlers around or after 1832, like *Bos taurus*, *Equus caballus*, *E. asinus* and *Sus scrofa* (and *Capra hircus* in 1685), which later turned feral (Heyerdahl and Skolsvod 1956, Jiménez-Uzcátegui et al. 2007). Vertebrate introductions have decreased with the implementation of a quarantine and inspection system (Zapata 2008).	Stable
(3) Transport-**Contaminant**	Food contaminant (including of live food)	High	At least 91 invertebrate species were introduced on food items, 42 of these on fruits and vegetables and 49 in stored products (C. Causton, unpubl. data). Many of these are intercepted regularly.	Increasing
	Parasites on animals (including species transported by host and vector)	High	76 pathogens and parasites have been brought to Galapagos on or in animals (37 pathogens and 39 terrestrial invertebrates). These include viruses in chickens, cats and dogs (Deem et al. 2008, 2011), several lice species (Palma and Peck 2013) and parasitoid wasps (Peck et al. 1998), among others. Thirty of these species are only known to coexist with introduced animals (Toral-Granda et al. 2017). Obtaining more information on the distribution of the remaining parasites and their impacts on wildlife and pathogens, is a priority for research (Anonymous 2015).	Increasing
	Contaminant on plants (except parasites, species transported by host/vector)	High	At least 207 invertebrate species were very likely transported to Galapagos as contaminants on plants. Multiple species of *Hemiptera* are thought to have been introduced through this pathway and many of these are known pests and/or vectors of diseases (Causton et al. 2006).	Increasing
	Parasites on plants (including species	High	At least 26 plant pathogens have been introduced to Galapagos, for example *Asperisporium caricae* and *Hemileia vastatrix*,	Increasing

	transported by host and vector)		probably on papaya and coffee (Cannon et al. 2014). Archipelago-wide surveys are still needed for this pathway.	
	Seed contaminant	Medium to High	Currently, there are 127 plant species that likely have reached Galapagos as seed contaminants, in particular, as contaminants of crop seeds (Musil 2015, Wilson et al. 2016), like *Eleusine indica*, *Leersia hexandra*, *Achyranthes aspera*, *Nicandra physalodes* (Bungartz et al. 2014) and many more. With the quarantine system in place, the risk of the introduction of seed contaminants should decrease. However, there is evidence that species are still (accidently) being brought in by seeds.	Stable to Increasing
	Timber trade	Low	13 terrestrial invertebrate species are recorded as having been introduced in wood or construction material (not necessarily through 'timber trade'), including the beetles *Xyleborinus gracilis* and *Carphina arcifera* (Peck 2006). Most of these are associated with dead trees and do not cause damage to living trees. However, pallets used for transporting materials to Galapagos are a problem if the International Standards for Phytosanitary Measures (ISPMs) are not followed.	Stable
	Transportation of habitat material (soil, vegetation...)	Low	In total, 130 terrestrial invertebrates have likely been introduced to Galapagos on habitat material, like the tropical fire ant *Solenopsis geminata* (Wauters et al. 2014). Since the implementation of a biosecurity system in 2000, this pathway has been reduced considerably (Zapata 2008).	Stable
(4) Transport-**Stowaway**	Container/bulk	High	Since 2015, cargo that is not air freight is being transported from mainland Ecuador (from the harbour of Guayaquil) to Galapagos in large containers. This system was implemented by the government of Galapagos to reduce the risk of accidentally transporting new organisms to the island (Toral-Granda et al. 2017). Current infrastructure for packing and inspecting cargo in containers in Guayaquil is not sufficient to guarantee that species are not transported in these containers. The government of Galapagos is leading efforts to raise funds to create infrastructure conditions that guarantee the biosecurity for Galapagos. An analysis of the risks of this pathway is underway.	Increasing
	Hitchhikers in or on a plane	Medium	Many species have been reported as stowaways on planes, and it is likely there are many more unrecorded cases that have come via this pathway. Know cases include, the saffron finch *Sicalis flaveola,* intercepted at the airport of Baltra in 2014, the highly invasive Argentine ant (*Linepithema humile*) (Toral-Granda et al 2017), and the southern house mosquito, *Culex quinquefasciatus*, a potential vector of West Nile Virus and Malaria, has been intercepted on several occasions since it was first recorded in 1985 (Causton et al. 2006; Bataille et al. 2009). Biosecurity inspections, fumigation of planes, and regular monitoring is now carried out by the GBA to prevent new species introductions via planes, but interceptions are still occurring (Toral-Granda et al. 2017) (see 4. Management status).	Stable
	Hitchhikers on ship/boat (excluding ballast water and hull fouling)	Very high	There are 29 species that have been reported as having been introduced as hitchhikers, but there are likely many more. About half of the detected species were invertebrates and 11 species were vertebrates, including multiple introductions of the green iguana and the introduction of an Ecuadorian milk snake *Lampropeltis micropholis* (Toral-Granda et al. 2017, Cisneros-Heredia 2018). The very invasive *Rattus rattus* arrived to Galapagos through this pathway in the 1600s and *Rattus norvegicus* in 1983 (Phillips 2012). Boats must be fumigated and biosecurity inspections are carried out (Zapata 2008), but infrastructure is insufficient to cope with the increasing quantity of cargo shipped (see 4. Management status). Boats that travel within Galapagos are vectors of native and non-native insects,	Increasing

			primarily through attraction to boat lights (Roque-Albelo et el. 2008) and measures were put in place by the GNPD to reduce this risk. Funds are needed to evaluate the efficacy of these measures.	
	Hitchhiker on transport vehicles/cargo*	High	There are 99 species that have likely come to Galapagos on boats or planes as stowaways or as stowaways in cargo that was shipped on these transport vehicles. Most of these species are invertebrates but also include six amphibians and reptiles, such as the tree frog *Scinax quinquefasciatus* (Jiménez-Uzcátegui et al. 2007).	Increasing
	Machinery/ equipment	Low	Biosecurity measures in place.	Stable
	People and their luggage/equipment (in particular tourism)	High	People are inspected by the GBA at air and seaports in mainland Ecuador and Galapagos. An evaluation of the efficacy of biosecurity inspections in 2008 revealed that a large number of invertebrates were entering the islands in personal luggage (Zapata 2008). With the increasing number of tourists entering Galapagos and the increase in the resident population, threats through this pathway are increasing (Toral-Granda et al. 2017).	Increasing
	Ship/boat ballast water and hull fouling	High	Since it is very difficult to determine whether a species was introduced to Galapagos through ballast water or attached to a ship or boat hull, the two vectors are treated together. According to the latest study, 49 previously unrecorded marine species were brought in either by ballast water or attached to the hull or both (Carlton et al. 2019). One species was likely brought to Galapagos in solid ballast (Carlton et al. 2019). Until recently, there were no biosecurity measures in place to reduce the risks of these pathways. Now, as per GBA regulation, all boats are required to have a clean hull prior to entering Galapagos waters.	Increasing
(5) **Corridor**	Interconnected waterways/basins/seas Tunnels and land bridges	Zero	Galapagos does not have interconnected waterways, tunnels or land bridges. It has been proposed in the past to connect the airport on Baltra island by bridge to the island of Santa Cruz but there are currently no plans to carry this out.	Stable
(6) **Unaided by humans**	Natural dispersal across borders of IAS that have been introduced through pathways 1–5	High	Evidence suggests that there are several introduced species that are transporting introduced or invasive species within the archipelago, such as the invasive smooth-billed ani *Crotophaga ani*, which feeds on the highly invasive blackberry *Rubus niveus* and probably disperses the seeds between islands (Connett et al. 2016). The extent of this has not been evaluated. Furthermore, dogs were exposed to many pathogens found in mainland South America, like the canine distemper virus, which could potentially affect the Galapagos sea lion (Levy et al. 2008). Ecuadorian penal code now prohibits the euthanising of stray cats and dogs (COIP 2018), increasing the risk of diseased animals spreading viruses.	Increasing
(7) **Unknown**	Introduction vector unknown	Unknown	There are 29 introduced terrestrial and 4 marine species, for which the introduction pathways are not known (Total-Granda et al. 2017, Carlton et al. 2019).	Unknown

*Category ((7) unknown) was added as Galapagos-specific according to Toral-Granda et al. 2017. This was because for many of the species, the specific mode of transport was not identified, or it was hard to distinguish whether the species was a stowaway in cargo or the vehicle itself.
Abbreviation used: GBA = Galapagos Biosecurity Agency; GNPD = Galapagos National Park Directorate.

Trends: Due to increases in resident populations and tourism the overall prevalence of pathways is **increasing**.

2. Species inventory
The latest review indicates that there are 1 522 introduced terrestrial and marine species established in the archipelago (Toral-Granda et al. 2017, Carlton et al. 2019). These include 810 terrestrial plants (270 naturalised, 534 human-dependent, 6 with unknown status), 499 insects, 70 terrestrial invertebrates (other than insects), 63 pathogens, 27 vertebrates, 50 marine invertebrates and 3 marine plants. In addition, there are 103 species listed that were either intercepted, eradicated or never established. Of the established species, at least 60 are considered invasive transformer species (Atkinson et al. 2011, Gardener et al. 2013).

Trends: The number of species entering and being recorded in Galapagos is still **increasing** over time with strong evidence of this reported in Toral-Granda et al. (2017).

3. Impacts
In 2011, at least 60 species were identified as highly invasive and to have impacts in Galapagos, most were plants (32), followed by vertebrates (22) and insects (6) (Atkinson et al. 2011). This list is currently being revised and updated due to the change in status of many taxa, e.g. marine invertebrates and pathogens (Toral-Granda et al. 2017, Carlton et al. 2019). The top-ten worst invasive species in Galapagos in terms of impacts are *Cedrela odorata*, *Felis catus*, *Philornis downsi*, *Polistes versicolor, Psidium guajava*, *Rattus rattus*, *Rattus norvegicus*, *Rubus niveus*, *Solenopsis geminata* and *Wasmannia auropunctata*. Plant species with demonstrated localised negative impacts on biodiversity and ecosystem services include *Cedrela odorata*, *Cestrum auriculatum*, *Cinchona pubescens, Lantana camara*, *Psidium guajava*, *Rubus niveus* and *Tradescantia fluminensis* (Watson et al. 2009, Rentería et al. 2013, Jäger 2015, Jäger et al. 2017, Rivas-Torres et al. 2018). There are also around 100 'potential transformer species' that need further assessment, such as *Cleome viscosa, Leucaena leucocephala*, *Pennisetum purpureum*, *Piper peltatum*, *Sida rhombifolia* and many more (Gardener et al. 2013).

Introduced mammals have had the biggest negative impacts on Galapagos species and ecosystems. Species exerting current and serious threats to the Galapagos biodiversity include *Canis lupus familiares, Felis catus, Rattus rattus*, *Rattus norvegicus* and *Sus scrofa* (Jiménez-Uzcátegui et al. 2007, Phillips et al. 2012). Other vertebrates that are affecting Galapagos ecosystems include the smooth-billed ani, *Crotophaga ani* and the introduced treefrog *Scinax quinquefasciatus.* The ani feeds on large numbers of invertebrates and fruits and possibly has aided the dispersal of invasive plants, such as *Rubus niveus* (Connett et al. 2016). It has also been reported to feed on an endemic racer snake and scorpion (Cooke et al. 2020). The treefrog, the only known amphibian in Galapagos, is a predator of invertebrates (Vintimilla 2005).

Of the large number of non-native insects and other terrestrial invertebrates in Galapagos (Toral-Granda et al. 2017), a few are highly invasive and widespread, such as the avian parasitic fly *Philornis downsi* and the tropical fire ant *Solenopsis geminata* (Wauters et al. 2014, Fessl et al. 2017). The blood-sucking larvae of *P. downsi* parasitize almost all small endemic land bird species (including Darwin's finches), causing their decline (Fessl et al. 2017). *Solenopsis geminata* feeds on eggs of endemic butterflies and attacks juvenile reptiles and birds, including threatened species like the giant tortoise, the Galapagos petrel and the Galapagos penguin (Wauters et al. 2014). Other introduced *Hymenoptera* with extensive impacts on biodiversity are the little fire ant *Wasmannia auropunctata* and the yellow paper wasp *Polistes versicolor* (Causton and Sevilla 2006). As with *Solenopsis*, the stings of *W. auropunctata* affect juvenile reptiles and birds and it predates on other invertebrates (Causton and Sevilla 2006). However, there is strong evidence that *W. auropunctata* is being replaced by *S. geminata* (Wauters et al. 2014; Jäger et al. 2019). *Polistes versicolor* is widely distributed around the archipelago and is a voracious predator of invertebrates (Parent 2000, Causton et al. 2006).

Although little is known about plant and animal pathogens that have been introduced to Galapagos, several pathogens have been found in domestic poultry on the islands, such as the Avian paramyxovirus and adenovirus, and *Mycoplasma gallisepticum* (Deem et al. 2008; Deem et al. 2011). The avipoxvirus, introduced in the late 1890s, is threatening many Galapagos bird populations (Parker et al. 2011).

Lastly, the detection of the bryozoan *Amathia verticillata* at several locations within the harbour bay of Santa Cruz island is worrisome because of its proven negative impacts in other parts of the world (McCann et al. 2015, Carlton et al. 2019).

Trends: The overall impacts of IAS are still **increasing** in Galapagos.

4. Management

Between 2002 and 2011, a project entitled "The control of invasive species in the Galapagos Archipelago" was undertaken by the Ecuadorian Ministry of the Environment (Coello and Saunders 2011). This project had funding from the Global Environment Facility (a total of US$18.65 million), with counterpart and/or matching funding of US$32.5 million from the Galapagos National Park Directorate, the Charles Darwin Foundation, the Government of Ecuador, the German Government and other institutions (Coello and Saunders, 2011). A new plan for the management of the terrestrial and marine areas of the Galapagos National Park was formalised in 2014 (DPNG, Dirección del Parque Nacional Galapagos 2014), with an annual budget of about US$ 2.5 million for the control of invasive species (Christian Sevilla, pers. comm.). This includes an early detection and rapid response strategy for newly detected alien species in the National Park area. Furthermore, the 2007 Galapagos Invasive Species Management Plan was recently reviewed and updated through a participatory process ("Plan for the prevention, early detection, monitoring, control and eradication of invasive species in the Galapagos Islands", Fondo de Inversión Ambiental Sostenible 2018). This plan addresses the introduction, dispersal and establishment of invasive species and their harmful effects, for which coordinated actions by public institutions and national and international stakeholders are required. It is a public policy instrument that offers strategic guidelines for coordinated institutional action for the management of invasive species. Based on this plan, the different executing entities must design their operational planning to ensure the coordination of actions with counterparts identified for each strategic action.

To prevent additional introductions, the Ecuadorian government implemented a biosecurity protocol for Galapagos in 1999 (Zapata 2008) and established the Galapagos Biosecurity Agency (GBA) in 2012 (Toral-Granda et al. 2017). The GBA determines biosecurity regulations for inhabitants, visitors and scientists. It also carries out routine and spot biosecurity checks of passengers and cargo, as well as planes and boats that travel to the islands or between the islands. Regulations are in place to ensure that all planes and boats that visit Galapagos are fumigated (Toral-Granda et al. 2017). However, recent results have shown that despite these biosecurity measures, new species continue to arrive in Galapagos, including some known high impact invasive species (Toral-Granda et al. 2017). In 2015 and 2016, the GBA confiscated 14,180 products during routine inspections of passengers, luggage and cargo at air and seaports in mainland Ecuador and Galapagos. Of these, 48% were products that are prohibited from entering Galapagos because they pose a threat themselves or are vectors of alien species, 36% were restricted (did not meet specific quarantine and biosecurity requirements), 11% were in poor condition and 5% were infested with pests. No information about the type of products that were confiscated or the pests associated with these products was available for 2015; however, data for 2016 showed that numerous attempts were made to introduce fruits, seeds or plant species that are prohibited from entering Galapagos, including nine species that are not currently registered as being present. Confiscation data by GBA showed that of people bringing in non-permitted produce to Galapagos during the years 2015 and 2016, 69% were tourists (Ecuadorian and foreign) and 31% were Galapagos residents (Toral-Granda et al. 2017)**.**

There has been successful control of established species at different periods under the different plans mentioned above. Feral *C. hircus, Equus asinus* and *S. scrofa* have been eradicated on most of the islands in the archipelago, except on the inhabited islands of Santa Cruz, San Cristóbal and Isabela (Atkinson et al., 2011, Carrión et al. 2011). *Rattus rattus* has been eradicated on several smaller islands (Rueda et al. 2016). The rock pigeon *Columba livia* was eradicated from inhabited islands and *W. auropunctata* was thought to have been eradicated from one of the islands until a colony in another part of the island was detected (Atkinson et al. 2011). Tilapia *Oreochromis niloticus* had been released in the only freshwater lake in Galapagos on San Cristóbal island and was eradicated in 2007, with the eradication confirmed in 2010 (Phillips et al. 2012). Plant species with small populations have also been eradicated, including kudzu *Pueraria phaseoloides* var. *javanica* and a species of *Opuntia*, both notorious invaders in other regions of the world (Buddenhagen and Tye 2015). However, some of the eradication project goals could not be met because of insufficient funds or lack of permission of landowners to access invaded private properties (Gardener et al. 2009, but see Buddenhagen and Tye 2015, Atkinson et al. 2011).

For other key high threat IAS, such as *Philornis downsi*, *Solenopsis geminata*, *Rubus niveus* and *Psidium guajava*, effective management techniques are still not available (though some are under investigation). These species continue to seriously affect the unique biodiversity and ecosystems of this oceanic archipelago. The impacts of one invasive insect, the cottony cushion scale *Icerya purchasi*, have been permanently reduced through the introduction of the biological control agent, the vedalia beetle *Rodolia cardinalis* (Calderón Alvarez et al. 2012, Hoddle et al. 2013).

Assessment: While important steps have been made to improve management effectiveness of IAS in Galapagos, some challenges remain and therefore, the site can be categorised as **some concern**.

Trends: Management capacity and response effectiveness is **increasing**.

5. Predictions on future threats/needs

The threats caused by the introduction of new parasites, pathogens and disease vectors have increased over the last 20 years due a rapidly growing local population and the ever-increasing tourism industry (Bataille et al. 2018). Galapagos has two airports and several ship ports and further introduction of disease vectors, dieseases and parasites through pathways associated with these is of major concern (Toral-Granda et al. 2017, Bataille et al. 2018). The increase in accidental introductions of species as contaminants or stowaways of concern (Toral-Granda et al. 2017).

The biosecurity agency GBA needs to be better funded to be able to prevent further introductions to the islands, especially given the current increase in tourism and greater connectivity between the different Galapagos Islands, including uninhabited ones (Toral-Granda et al. 2017). Furthermore, emphasis should be placed on minimizing ports of entry to Galapagos (currently only enforced on Guayaquil and Quito) to enable focused biosecurity efforts and to reduce connectivity with other geographic locations, as recommended by UNESCO-IUCN (2006). Better management techniques for some high impact IAS are still needed, if they are to be sustainable in the long run.

Trends: The threat of future biological invasions is still **increasing**; future management is **capable** of dealing with many of them.

6. Knowledge status and gaps

Indicator	Status of knowledge	Confidence	Notes and recommendations
1. Introduction pathways	High	High	A thorough analysis of pathways of species introductions to Galapagos was carried out in 2017 (Toral-Granda et al. 2017).
2. Species inventories	Moderate	High	Lists for introduced species were last updated in 2017 and new species are continuously being added. The list of invasive species within these lists is currently being updated. However, there are still several taxonomic groups that still have not been surveyed (Bungartz et al. 2012).
3. Impacts of IAS	Moderate	High	Impacts are known for some of the most invasive species, like *Philornis downsi*, *Rattus rattus*, *Rubus niveus* and *Cinchona pubescens*, but evidence is lacking for many other species. Impacts of species like *Felis catus* or *Psidium guajava*, are assumed from assessments carried out elsewhere in the world.
4. Management status	Moderate	High	Currently, effective management actions are carried out to control or eradicate six of the ten most invasive species from some of the islands (see 4. Management status). But management plans for the remaining species, as well as for less invasive species, are still lacking.
5. Future threats	Moderate	High	Toral-Granda et al 2017 showed that new or already known introduced or invasive species are still reaching the islands, despite the biosecurity system implemented in the islands. Risk analyses were conducted to identify high threat invertebrate species (Rogg et al. 2003), contingency plans available for some high threat diseases (e.g. West Nile Virus, Eastwood et al. 2014).

7. Overall assessment

The overall threat level of IAS to the values and integrity of the Galapagos Islands was determined to be **Very high threat**. Much-needed surveys of terrestrial and marine ecosystems are expected to result in the inclusion of additional species in the invasive species list. In spite of considerable efforts and many successes by the Government of Ecuador to protect the borders of Galapagos from the introduction of new species, the number of visitors, flights, boats and cargo transported to Galapagos are increasing exponentially and with this, the risk of new species arriving and spreading.

Trends: The overall threats for the Galapagos Islands are **increasing**.

References

Anonymous (editor) (2015) Workshop to develop an action plan for health contributions to conservation in the Galapagos. Health contributions to conservation in the Galapagos: A strategic action planning workshop; Santa Cruz Island, Galapagos, Ecuador.

Atkinson R, Gardener M, Harper G, Carrión V (2012) 50 years of eradication as a conservation tool in Galapagos: what are the limits? In: Wolff M, Gardener M (eds) The role of science for the conservation of the Galapagos: a 50 year experience and challenges for the future, Routledge, Oxford, pp. 183–198.

Bataille A, Cunningham AA, Cedeño V, Patiño L, Constantinou A, Kramer LD Goodman SJ (2009) Natural colonization and adaptation of a mosquito species in Galapagos and its implications for disease threats to endemic wildlife. Proc Nat Acad Sci USA 106: 10230-10235.

Bataille A, Levin II, Sari EHR (2018) Colonization of Parasites and Vectors. In: Parker, P. (eds) Disease Ecology. Social and Ecological Interactions in the Galapagos Islands. Springer, Cham, pp. 45-79.

Buddenhagen CE, Tye A (2015) Lessons from successful plant eradications in Galapagos: commitment is crucial. Biol Invasions 17: 2893–2912.

Bungartz F, Herrera H, Jaramillo P, Tirado N, Jiménez-Uzcátegui G, Ruiz D, Guézou A, Ziemmeck F (2014) Charles Darwin Foundation Galapagos Species Checklist - Lista de Especies de Galapagos de la Fundación Charles Darwin. Charles Darwin Foundation / Fundación Charles Darwin, Puerto Ayora, Galapagos.

Bungartz F, Ziemmeck F, Tirado N, Jaramillo P, Herrera H Jiménez-Uzcátegui (2012) The neglected majority: Biodiversity inventories as an integral part of conservation biology. In: Wolff M, Gardener M (eds) The role of science for the conservation of the Galapagos: a 50 year experience and challenges for the future, Routledge, Oxford, pp 119–142.

Calderón Alvarez C, Causton CE, Hoddle MS, Hoddle CD, van Driesche R, Edward J. Stanek III EJ (2012) Monitoring the effects of *Rodolia cardinalis* on *Icerya purchasi* populations on the Galapagos Islands BioControl 57: 167-179.

Campbell K, Donlan CJ, Cruz F, Carrión V (2004) Eradication of feral goats *Capra hircus* from Pinta Island, Galapagos, Ecuador. Oryx 38: 328–333.

Cannon P, Arboleda F, Evans HC, Bungartz F (2014) CDF Checklist of Galapagos Phytopathogenic Fungi - FCD Lista de especies de Hongos Fitopatógenos de Galapagos. In: Bungartz F, Herrera H, Jaramillo P, Tirado N, Jiménez-Uzcátegui G, Ruiz D, Guézou A, Ziemmeck F (eds). Charles Darwin

Foundation Galapagos Species Checklist - Lista de Especies de Galapagos de la Fundación Charles Darwin. Charles Darwin Foundation / Fundación Charles Darwin, Puerto Ayora, Galapagos.

Carlton JT, Keith I, Ruiz GM (2019) Assessing marine bioinvasions in the Galapagos Islands: implications for conservation biology and marine protected areas. Aquat Invasions 14: 1-20.

Campbell ML, Keith I, Hewitt CL, Dawson TP, Collins K (2015) Evolving marine biosecurity in the Galapagos Islands. Manage Biol Invasions 6: 227-230.

Carrión V, Donlan CJ, Campbell KJ, Lavoie C, Cruz F (2011) Archipelago-wide island restoration in the Galapagos Islands: reducing costs of invasive mammal eradication programs and reinvasion risk. PLoS ONE 6: Article e18835.

Causton CE, Sevilla C (2006) Latest Records of Introduced Invertebrates in Galapagos and Measures to control them. Galapagos Report 2006-2007, CDF, GNP and INGALA, Puerto Ayora, Galapagos, Ecuador, pp. 142-145.

Causton CE, Peck SB, Sinclair BJ, Roque-Albelo L, Hodgson CJ, Landry B (2006) Alien Insects: Threats and Implications for Conservation of Galapagos Islands. Ann Entomol Soc Am 99: 121–143.

Cisneros-Heredia DF (2018) Non-native small terrestrial vertebrates in the Galapagos. PeerJ 6: e26563v1.

Coello S, Saunders A (2011) Final project evaluation, Control of invasive species in the Galapagos Archipelago, ECU/00/G31. Prepared for the Global Environment Fund (GEF) - United Nations Development Programme (UNDP) - Ministry of the Environment (MAE): 107 pp. + 12 Annexes.

COIP (2018) Código Orgánico Integral Penal del Ecuador, https://www.defensa.gob.ec/wp-content/uploads/downloads/2018/03/COIP_feb2018.pdf (last accessed: 30 January 2020)

Connett L, Guézou, A, Herrera HW, Carrión V, Parker PG, Deem SL (2016) Gizzard contents of the Smooth-billed Ani *Crotophaga ani* in Santa Cruz, Galapagos Islands, Ecuador. Galapagos Res 68: 43-48.

Convention of Biological Diversity (2014) Pathways of introduction of invasive species, their prioritization and management. Note by the Executive Secretary. Montreal, 23-28 June 2014.

Cooke SC, Anchundia D, Caton E, Haskell LE, Jäger H, Kalki Y, Mollá O, Rodríguez J, Schramer TD, Walentowitz A, Fessl B (2020) Endemic species predation by the introduced smooth-billed ani in Galápagos. Biol Invasions 22: 2113–2120.

Deem SL, Cruz M, Jiménez-Uzcátegui G, Fessl B, Miller E, Parker PG (2008) Pathogens and parasites: an increasing threat to the conservation of Galapagos. Galapagos Report 2007-2008. FCD, PNG & INGALA. Puerto Ayora, Ecuador. pp. 136–141.

Deem SL, Cruz MB, Higashiguchi JM, Parker PG (2011) Diseases of poultry and endemic birds in Galapagos: implications for the reintroduction of native species. Anim Conserv 15: 73-82.

Dirección del Parque Nacional Galápagos (2014) Plan de Manejo de las Áreas Protegidas de Galapagos para el Buen Vivir. Puerto Ayora, Galápagos, Ecuador.

Eastwood G, Goodman S, Hilgert N, Cruz M, Kramer L, Cunningham A (2014) Using Avian Surveillance in Ecuador to Assess the Imminence of West Nile Virus Incursion to Galapagos. EcoHealth 11: 10.1007/s10393-014-0911-5.

Fessl B, Heimpel GE, Causton CE (2018) Invasion of an avian nest parasite, *Philornis downsi*, to the Galapagos Islands: colonization history, adaptations to novel ecosystems, and conservation challenges. In: Parker PG (ed), Disease Ecology, Social and Ecological Interactions in the Galapagos Islands. Springer International Publishing AG. pp. 213-268.

Fondo de Inversión Ambiental Sostenible (2018) Plan de Manejo de Especies Invasoras para Galápagos (2019-2019).

Gardener MR, Atkinson R, Rentería JL (2009) Eradications and people: lessons from the plant eradication program in Galapagos. Restor Ecology 18: 20-29.

Gardener MR, Trueman M, Buddenhagen C, Heleno R, Jäger H, Atkinson R, Tye A (2013) A pragmatic approach to the management of plant invasions in Galapagos. In: Foxcroft LC, Pyšek P, Richardson DM, Genovesi P (eds) Plant Invasions in Protected Areas: Patterns, Problems and Challenges. Springer Netherlands, Dordrecht, pp. 349–374. doi: 10.1007/978- 94-007-7750-7_16

Heyerdahl T, Skolsvod A (1956) Archeological evidence of pre-Spanish visit to the Galapagos Islands. Am Antiq 22: 1-71.

Hickman CP, Zimmerman TL (2000) A field guide to crustaceans of Galapagos. Sugar Spring Press, Lexington, Virginia, pp. 156.

Hoddle M, Crespo Ramírez C, Hoddle CD, Loayza J, Lincango MP, Van Driesche RG, Causton CE (2013) Post release evaluation of *Rodolia cardinalis* (Coleoptera: Coccinellidae) for control of *Icerya purchasi* (Hemiptera: Monophlebidae) in the Galapagos Islands. Biol Control 67: 262-274.

IUCN/UNESCO Mission Report (2006). Galapagos Islands (Ecuador) (1 bis) // Îles Galapagos (Équateur) (1 bis). February 28 – March 10, 2006.

Jäger H, Buchholz S, Cimadom A, Tebbich S, Rodríguez J, Barrera D, Walentowitz A, Breuer M, Carrión A, Sevilla C, Causton C (2017) Restoration of the blackberry-invaded Scalesia forest: Impacts on the vegetation, invertebrates, and birds. In: Galapagos Report 2015-2016. DPNG, CGREG, CDF and GC. Puerto Ayora, Galapagos, Ecuador. pp. 142-148.

Jäger H, Crespo C, Abad F, Llerena A, Couenberg P (2019) Learning from farmers: invasive species in the agricultural lands of Santa Cruz. In: Galapagos Report 2017-2018. GC. Fairfax, VA. pp. 63-66.

Jäger H (2015) Biology and Impacts of Pacific Island Invasive species. 11. *Cinchona pubescens* (Red Quinine Tree) (Rubiaceae). Pacific Sci 69: 133-153.

Jiménez-Uzcátegui G, Zabala J, Milstead B, Snell HL (2015) CDF Checklist of Galapagos Introduced Vertebrates. Charles Darwin Foundation: Puerto Ayora, Galapagos: http://www.darwinfoundation.org/datazone/checklists/introduced-1397 species/introduced-vertebrates/

Jiménez-Uzcátegui G, Carrión V, Zabala J, Buitrón P, Milstead B (2007) Status of introduced vertebrates in Galapagos. Galapagos Report 2006–2007. Charles Darwin Foundation, Puerto Ayora, pp. 136–141.

Levy JK, Crawford PC, Lappin MR, Dubovi EJ, Levy MG, Alleman R, Tucker SJ, Clifford EL (2008) Infectious diseases of dogs and cats on Isabela Island, Galapagos. J Vet Intern Med 22: 60-65.

McCann L, Keith I, Carlton JT, Ruiz GM, Dawson TP, Collins K (2015) First record of the non-native bryozoan *Amathia* (*Zoobotryon*) *verticillata* (delle Chiaje, 1822) (Ctenostomata) in the Galápagos Islands. BioInvasions Rec 4: 255-260.

Musil AF (2015) Identification of crop and weed seeds. Scientific Publishers, pp. 214.

Palma RL, Peck SB (2013) An annotated checklist of parasitic lice (Insecta: Phthiraptera) from the Galapagos Islands. Zootaxa 3627: 18–19.

Parent CE (2000) Life-cycle and ecological impact of *Polistes versicolor versicolor* (Olivier) (Hymenoptera: Vespidae): an introduced predatory wasp on the Galapagos Islands, Ecuador. MS Thesis. Carleton University, Canada.

Parker PG, Buckles EL, Farrington H, Petren K, Whiteman NK, Ricklefs RE, Bollmer JL, Jiménez-Uzcátegui G (2011) 110 Years of Avipoxvirus in the Galapagos Islands. PLoS ONE 6: e15989.

Peck SB (2006) The Beetles of the Galapagos Islands, Ecuador: Evolution, Ecology, and Diversity (Insecta: Coleoptera) NRC Research Press, Ottawa, Ontario, Canada. pp. 314.

Peck SB, Heraty J, Landry B Sinclair BJ (1998) Introduced insect fauna of an oceanic archipelago: The Galapagos Islands, Ecuador. Am Entomol 44: 218-237.

Phillips RB, Wiedenfeld DA, Snell HL (2012) Current status of alien vertebrates in the Galapagos Islands: invasion history, distribution, and potential impacts. Biol Invasions 14: 461–480.

Rentería JL, Gardener MR, Panetta FD, Atkinson R, Crawley MJ (2012) Possible impacts of the invasive plant *Rubus niveus* on the native vegetation of the *Scalesia* forest in the Galapagos Islands. PLoS ONE 7: e48106.

Rivas-Torres G, Luke Flory S, Loiselle B (2018) Plant community composition and structural characteristics of an invaded forest in the Galapagos. Biodiv Conserv 27 329-344.

Rogg H, Buddenhagen C, Causton C (2005) Experiences and limitations with pest risk analysis in the Galapagos Islands. In: Identification of risks and management of invasive alien species using the IPPC framework. Proceedings of the Workshop on Invasive Alien Species and the International Plant Protection Convention. International Plant Protection Convention Secretariat, Braunschweig, Germany, pp. 798– 807.

Rueda D, Campbell KJ, Fisher P, Cunninghame F, Ponder JB (2016) Biologically significant residual persistence of brodifacoum in reptiles following invasive rodent eradication, Galapagos Islands, Ecuador. Conserv Evid 13: 38.

Toral-Granda MV, Causton CE, Jäger H, Trueman M, Izurieta JC, Araujo E, Cruz M, Zander KK, Izurieta, A, Garnett ST (2017) Alien species pathways to the Galapagos Islands, Ecuador. PLoS ONE 12: e0184379.

Vintimilla JE (2005) Estudios para el control y disminución de ranas *Scinax quinquefasciatus*, con impactos minimos en los Humedales de Isabela Sur (Islas Galápagos). Tesis previa la obtención del titulo de Ingeniero Agrónomo. Universidad de Cuenca. Cuenca, Ecuador. pp 71.

Watson J, Trueman M, Tufet M, Henderson S, Atkinson R (2009) Mapping terrestrial anthropogenic degradation on the inhabited islands of the Galapagos Archipelago. 2009. Oryx 44: 79-82.

Wauters N, Dekoninck W, Herrera HW, Fournier D (2014) Distribution, behavioral dominance and potential impacts on endemic fauna of tropical fire ant *Solenopsis geminata* (Fabricius, 1804) (Hymenoptera: Formicidae: Myrmicinae) in the Galapagos archipelago. Pan-Pacific Entomol 90: 205-220.

Wilson CE, Castro KL, Thurston GB, Sissons A (2016) Pathway risk analysis of weed seeds in imported grain: A Canadian perspective. In: Daehler CC, van Kleunen M, Pyšek P, Richardson DM (Eds) Proceedings of 13th International EMAPi conference, Waikoloa, Hawaii. NeoBiota 30: 49–74.

Zapata CE (2008) Evaluation of the Quarantine and Inspection System for Galapagos (SICGAL) after seven years. In: CDF, DPNG, INGALA, editors. Galapagos Report 2006-2007. Puerto Ayora, Galapagos, pp. 60-66.

4. Kakadu National Park (Australia)

1. Pathways

Pathways have not been fully assessed for Kakadu but there is a good understanding of potential pathways for the whole of Australia (Pheloung, 2003). National level biosecurity measures are good but there are no strict biosecurity measures in place at Kakadu. The lack of preventative measures in place suggest that there are key pathways that may result in further introduction of alien species, which mostly relate to accidental introductions or natural processes. Key pathways include natural dispersal, release in nature for biological control (this approach has been used previously for the site; see management section below), and all transport stowaway pathways especially contaminants/hitchhikers on modes of transport and equipment, and as a stowaway on tourists and their luggage. The corridor pathway and intentional release in nature (except for biological control) are not likely pathways for the site.

CBD Pathway Category	Subcategory	Risk	Examples and/or notes	Trends
(1) Release in nature	Biological control	Very high	Biological control agents have been released into Kakadu (e.g. *Cyrtobagous silviniae* to control *Silvina molesta* (Sullivan et al. 2011)). *Rhinella marina* is a failed biological control initiative in Australia and is likely to spread naturally into Kakadu. Australia has a prominent biological control program and more host specific and safely tested agents are very likely to be introduced in the future.	Stable
(2) Escape from confinement	Pets, ornamental/ horticultural plants and agricultural plants	High	A few pathways may be relevant including escaped pet species (e.g. *Felis catus*), ornamental plants (e.g. *Silvina molesta, Cryptostegia grandiflora*) and escaped agricultural species (in particular invasive grasses) as well as farmed animals (*e.g. Sus domesticus, Equus ferus caballus*).	Stable
(3) Transport-**Contaminant**	All	Low	The park is quite isolated and so introductions as contaminates are likely to be low. Many contaminates may be intercepted at points of entry through Australia's good biosecurity practises at borders. However, it is thought that *Mimosa pigra* could have first been introduced to Darwin as a seed contaminant and then later spread naturally from there into Kakadu (Vitelli et al. 2006)	Stable
(4) Transport– **Stowaway**	All	Very high	It is likely that all the sub-categories are relevant for introduction events by stowaway although exact examples are lacking.	Increasing
(5) Corridor	N/A	N/A	This pathway is not relevant.	N/A
(6) Unaided	Natural dispersal across borders of IAS that have been introduced through pathways 1–5	High	It is very likely many escaped species are spreading naturally and have entered the site by this means. For example, *Mimosa pigra* is likely to have entered the park though natural dispersal from Darwin. Of concern is the natural spread of *Rhinella marina*	Increasing

Trends: Pathway threats for the site appear to be **stable**, although the lack of site-specific biosecurity measures is of concern.

2. Species inventory

There are 60 known IAS in Kakadu. Of these there are 49 invasive alien plant species, seven invasive mammal species, one invasive amphibian species, one invasive invertebrate species and two invasive micro-organisms (Shackleton et al. 2020). These figures are based on up to date monitoring in the national park. Macdonald and Frame (1988) reported 67 invasive plant species in Kakadu and over 25 invasive mammals. Cowie and Werner (1993) recorded 89 invasive alien plant species. This data suggests a reduction in the number of invasive species since the 1980s. There have only been two plant eradications, suggesting that some of the species listed as invasive in 1993 were only alien or many species have died out naturally. The same can be assumed for mammals.

Trends: Overall, the number of species listed remains **stable** over time.

3. Impacts

Invasive plant species considered to be a major concern by managers include *Andropogon gayanus*, *Hymenachne amplexicaulis*, *Jatropha gossypiifolia, Mimosa pigra, Pennisetum polystachion, Pennisetum pedicellatum, Salvinia molesta, Themeda quadrivalvis*, and *Urochloa mutica* (Cowie and Werner, 1993; Finlayson et al. 2006, Setterfield et al. 2013). These species impact negatively on native biodiversity by changing ecosystem structure and function and through competition for limited resources. For example, *M. pigra* causes structural changes on the floodplains, changing the grass/sedgelands to shrubland, and *U. mutica* displaces native plant species though competition for space and resources (Bayliss et al. 2012). *Urochloa mutica* also detrimentally affects the nesting sites of bird species (Bayliss and Yeomans, 1990) and increases fire intensity. Mammals currently considered to pose major threats include *Bubalus bubalis* (water buffalo), *Sus domesticus* (pig), *Felis catus, Equus ferus caballus,* and *Equus africanus asinus,* and *Rattus rattus* is considered to be an emerging IAS. Grazing, trampling and wallowing by the introduced *B. bubalis* greatly reduces plant biomass, decreasing the available fuel for fires, thus altering fire ecology. *Bubalus bubalis* also causes extensive saltwater intrusion into freshwater swamps by damaging micro-levies separating fresh and saltwater and making water turbid though wallowing (McGregor et al. 2010). Similar impacts are caused by *S. domesticus* (Robinson et al. 2005). A number of these invasive mammalian species are reservoirs of non-native and endemic diseases and parasites, the most concerning of which are the Japanese encephalitis virus found in pig populations, and bovine tuberculosis, carried by buffalo. *Felis catus* and *R. rattus* predate on native biodiversity. *Apis mellifera* is thought to interfere with the pollination of plants dependent on native pollinators, thereby decreasing pollination rates and interfering with seed production (Vaughton, 1996).

Trends: Current threats from invasive plant and mammal species are **increasing** over time as highlighted by park managers and ecologists. The threats from other taxa are currently stable but could increase in the future if there are new introductions (see future threats below).

4. Management

In the past, management of IAS within the national park was often sporadic, poorly recorded and evaluations are far from comprehensive, but things have improved substantially in the past two decades. There is currently an official management plan for IAS in the park, which is updated every five years (the last one being formalised in 2017), and an annual budget of $ 800 000 for management.

There are currently no preventative measures in place to ensure that alien species do not enter the park, and there are no early detection rapid response programs in place. Invasive *F. catus* is monitored regularly.

A number of highly and potential highly threatening IAS are currently under some form of management (Setterfield et al. 2013). Successful eradications have taken place for the invasive plant species *Eichhornia crassipes* and *Parkinsonia aculeata.* Two invasive invertebrate ant species, *Pheidole megacephala* and *Solenopsis geminata*, are thought to be eradicated, although continued monitoring is needed (Hoffmann and O'Conner 2004). There are ongoing eradication attempts for A*ndropogon gayanus, Brachiaria mutica, Hymenachne amplexicaulis, Hyptis capitata* and *M. pigra*. There have been failed eradication attempts for a number of species (e.g. *A. gayanus, S. molesta, M. pigra and H. capitata*).

Mimosa pigra, A. gayanus, S. molesta, *F. japonica, H. amplexicaulis, P. pedicellatum, P. polystachion* and *Brachiaria mutica* are currently being managed in the national park with the goal of containment and impact reduction. Management attempts have had various degrees of success. For example, *M. pigra* is considered to be contained and/or declining in the park, with only a limited number of small infestations (although eradication was not successful), whereas *H. amplexicaulis* and *B. mutica* have spread extensively in recent years and now pose a substantial threat despite management (Setterfield et al. 2013). Integrated control of *S. molesta* has been fairly successful and populations are stable. Biological control of *S. molesta* using *Cyrtobagous silviniae* has shown variable success rates since it was adopted in the mid-1980s; success is quite dependent on rainfall and therefore there are cycles of good and bad control (Sullivan et al. 2011).

No invasive mammalian species are currently being managed, and invasions are increasing for most species.

Assessment: Overall, management can be categorised as facing **some concern**. There have been a few successes, as highlighted above, but many plants are still spreading despite management. Mammals also need to be managed in the future.

Trends: Management responses are **stable** over time.

5. Predictions on future threats/needs

Based on the expert opinion of managers, there are a few species that pose a potential threat. These include the emerging invasive plant species *Pennisetum setaceum*, *Cryptostegia grandiflora, Hyptis suaveolens* and *Senna obtusifolia*. The amphibian *Rhinella marina* presents a potential future threat as Kakadu is climatically suitable and the invasive species is spreading rapidly (Kearney et al. 2008). Although no reptile species are currently recorded as invasive, *Hemidactylus frenatus* and *Morelia spilota* are also potential future threats.

Introducing biosecurity would be beneficial as would the identification of management techniques to address species that are increasing substantially, especially invasive grasses. It is also important for the site to start managing the impacts of several mammal species which are currently not controlled. Further research into biological control for the broader region is recommended to improve sustainable management (Sutton et al. 2019).

Trends: Future threats of IAS are **increasing** both in terms of new arrivals and continued spread and impact of existing IAS, but current management appears to be **capable** of addressing them.

6. Knowledge status and gaps

Indicator	Status of knowledge	Confidence	Notes and recommendations
1. Introduction pathway prominence	Low	Low	No detailed assessments of pathways have been done for the WHS although they are well understood for Australia as a whole (Pheloung, 2003). Further work on this is needed.
2. Species inventories	High	High	The total number of IAS are known in the WHS and lists are updated but on an irregular basis and ad hoc. However, there is a good understanding of what species are currently present. There is also evidence of long-term trends based on species lists available from the 1980s (e.g. Macdonald and Frame, 1988; Cowie and Werner,1993).
3. Impacts of IAS	Moderate	High	Some research is taking place in the WHS and information on threats of prominent IAS at the site are also available from the literature. This gives a good indication of the impact the site faces from IAS (e.g. Bayliss and Yeomans 1990; Robinson et al. 2005; McGregor et al. 2010; Bayliss et al. 2012).
4. Management status	High	High	There is good information on the broad-scale status of management, although details are not available in a number of cases.
5. Future threats	Moderate	Moderate	Managers are aware of species that pose future threats, there is some evidence of their threat and potential for introduction, e.g. for cane toads. There is a need to highlight and prioritize future management needs.

7. Overall assessment

Based on the above assessment, Kakadu can be considered to face a **High threat** from IAS, which is the same threat rating it received in the 2017 World Heritage Outlook report (Osipova et al. 2017). There are several high-profile invasive species present, however, there is also the capacity to deal with many of them. Improved management of some species could help to lower the overall threat status.

Trends: Available evidence suggests that the overall threat is currently **stable**.

References

Bayliss P, Yeomans KM (1990) Seasonal distribution and abundance of magpie geese, *Anseranas semipalmata* Latham, in the Northern Territory, and their relationship to habitat, 1983–86. Aust Wildl Res 17:15–38.

Bayliss P, van Dam R, Bartolo R (2012) Quantitative ecological risk assessment of the Magela Creek floodplain in Kakadu National Park, Australia: comparing point source risks from the Ranger Uranium Mine to diffuse landscape-scale risks. Hum Ecol Risk Assess 18: 115–151.

Cowie ID, Wernerm PA (1993) Alien plant species invasive in Kakadu National Park, Tropical Northern Australia. Biol Conserv 63: 127-135.

Finlayson CM, Lowry J, Bellio MG, Nou S, Pidgeon R, Walden D, Humphrey C, Fox G (2006) Biodiversity of the wetlands of the Kakadu Region, northern Australia. Aquat Sci 68: 374-399.

Hoffmann BD, O'Connor S (2004) The successful eradication of the African big-headed ant (*Pheidole megacephala*) and the tropical fire ant (*Solenopsis geminata*) for Kakadu National Park. Ecol Manage Restor 5: 98-105.

Kearney M, Phillips BL, Tracy CR, Christian KA, Betts G, Porter WP (2008) Modelling species distributions without using species distributions: the cane toad in Australia under current and future climates. Ecography 31: 423-434.

Macdonald IAW, Frame GW (1988) The invasion of introduced species into nature reserves in tropical savannas and dry woodlands. Biol Conserv 44: 67-93.

McGregor S, Lawson V, Christophersen P, Kennett R, Boyden J, Bayliss P, Liedloff A, McKaige B, Andersen AN (2010) Indigenous Wetland Burning: Conserving Natural and Cultural Resources in Australia's World Heritage-listed Kakadu National Park. Hum Ecol 38; 721-729.

Osipova, E., Shadie, P., Zwahlen, C., Osti, M., Shi, Y., Kormos, C., Bertzky, B., Murai, M., van Merm, R. and Badman, T. 2017. IUCN World Heritage Outlook 2: A conservation assessment of all natural World Heritage sites. IUCN, Gland, Switzerland, 92 pp.

Pheloung, P (2003) An Australian perspective on the management of pathways for invasive species. In: Tuiz GM, Carlton JT (eds) Invasive species-vectors and management strategies. Island Press. Washington, USA. pp 249-269.

Robinson CJ, Smyth D, Whitehead PJ (2005) Bush tucker, bush pets, and bush threats: cooperative management of feral animals in Australia's Kakadu National Park. Conserv Biol 19: 1385-1391.

Setterfield SA, Douglas MM, Petty AM, Bayliss P, Ferdinands KB, Winderlich S (2013) Invasive plants in the floodplains of Australia's Kakadu National Park. In: Foxcroft LC, Pyšek P, Richardson DM, Genovesi P (Eds). Plant invasions in protected areas patterns, problems and challenges. Springer: Dordrecht. pp. 167-189.

Shackleton RT, Foxcroft LC, Wood LE, Pyšek P, Richardson DM (2020) Assessing biological invasions in protected areas: revisiting targeted nature reserves 30 years after the 1980s SCOPE programme. Biol Conserv 243: 108424.

Sullivan PR, Postle LA, Julien M (2011) Biological control of *Salvinia molesta* by *Cyrtobagous salviniae* in temperate Australia. Biol Control 57: 222-228.

Sutton GF, Canavan K, Day MD, den Breeyen A, Goolsby JA, Cristofaro M, McConnachie, A, Paterson ID (2019) Grasses as suitable targets for classical weed biological control. BioControl: 64: 605-622.

Vaughton G (1996) Pollination disruption by European honeybees in the Australian bird-pollinated shrub *Grevillea barklyana* (Proteaceae). Plant Syst Evol 200: 89-100.

Vitelli JS, Madigan BA, Worsley KJ (2006) *Mimosa pigra* in Queensland. In: 15th Australian Weeds Conference, Papers and Proceedings, Adelaide, South Australia, 24-28 September 2006: Managing weeds in a changing climate, Preston C, Watts JH, Crossman ND (eds). Victoria, Australia: Weed Management Society of South Australia, 251-254.

5. Keoladeo National Park (India)

1. Pathways

Pathways have not been assessed in detail for Keoladeo due to a lack of data. There are various pathways that might be prominent at the site, due to its close proximity to a densely populated town (Bharatpur) and high-intensity agriculture. Being a national park, new purposeful introduction events (release in nature) are not likely, and the corridor pathway is not applicable. However, in the past some species were purposefully introduced (released in nature). For example, *Prosopis juliflora* was introduced to augment fuelwood supply to local villages (Mukherjee et al. 2017). *Clarias gariepinus* was likely introduced to improve local aquaculture (https://timesofindia.indiatimes.com/city/jaipur/now-a-10-year-project-to-rid-keoladeo-of-african-catfish/articleshow/56138441.cms).

Possibilities for key pathways of introduction include: escape from confinement from nearby households and farms, as transport contaminants, as well as unaided natural dispersal (e.g. in the case of *Parthenium hysterophorus*). Most of the sub-categories relating to escape from confinement would be relevant (except for fur farms and botanical gardens/zoos). Furthermore, there is a high probability that species will be introduced as transport contaminants, especially on fishing equipment, as hitchhikers on transport vectors (boats, cars), or on machinery as well as on people (tourists).

CBD Pathway Category	**Subcategory**	**Risk**	**Examples and/or notes**	**Trends**
(1) Release in nature	Landscape improvement Fisheries Other (livelihood development)	High	*Prosopis juliflora* was purposely introduced to the site to aid local livelihoods in the vicinity (Mukherjee et al. 2017). Similarly, available information is vague but the fish *Clarias gariepinus* was likely purposefully introduced into the site for improved fishing. Although there is evidence of release in nature in the past, it is likely it will not occur again in the site due to the sites protected status.	Stable
(2) Escape from confinement	Agriculture Aquaculture Pet/aquarium species Farmed animals Forestry Horticulture Live bait	High	The sites proximity to a densely populated town (Bharatpur) and high intensity agriculture makes escape from confinement a key pathway. For example, the ornamental plants are likely to be escapees (e.g. *Eichhornia crassipes, Lantana camara,* is an escapee from agriculture *(Ipomoea aquatica, Paspalum distichum), aquaculture (Cyprinus carpio).* Many of these species may also have been introduced through natural dispersal	Unknown
(3) Transport-**Contaminant**	All	Low	The protected area is close to highly populated agricultural areas and a city. Alien species coming into the city and agricultural sites might be introduced as contaminants (especially though food, seed and timber and on animals) and then spread naturally into the site e.g. *Parthenium hysterophorus* that was likely introduced as a seed contaminant to India (McConnachie et al. 2011). Contaminants directly introduced into the site are unlikely.	Unknown
(4) Transport–**Stowaway**	All except for aeroplane, ballast water and packing material	High	No specific examples are available, but all species might be introduced and spread via most subcategories under transport stowaways except for aeroplanes, ballast water and packing material.	Increasing
(5) Corridor	N/A	N/A	Not relevant	n/a

(6) Unaided	Natural dispersal across borders of IAS that have been introduced through pathways 1–5	High	It is likely that may species have dispersed naturally from neighbouring regions.	Increasing

Trends: There is a lack of data to make inferences on trends in pathways; changes over time remain **unknown**.

2. Species inventory

Fourteen species are considered to be invasive in the Keoladeo National Park, although there are potentially more. No formal surveys have been undertaken in the WHS and data is based on expert consultation and literature searches. Plants are the most common invasive species (nine), followed by two fish (*Clarias gariepinus* and *Cyprinus carpio*), two mammals (*Bos taurus* and *Macaca mulatta*) and one insect (*Parapoynx diminutalis*). Over the last 30 years, *P. juliflora* has expanded considerably in the WHS, where it has become one of the dominant plant species in the area, posing many threats (Hockings et al. 2008; Mukherjee et al. 2017).

Trends: No long-term monitoring is in place and so trends are **unknown**, but it is likely that species numbers are increasing.

3. Impacts

A number of plant species, including *Eichhornia crassipes, Eleocharis plantaginea, Ipomoea aquatica, Lantana camara, Parthenium hysterophorus, Paspalum distichum, P. juliflora, Typha angustata,* and *Vetiveria zizanioides* have negative impacts. Such invasive plants replace native biota, deplete oxygen in the water bodies, interfere with water regimes, reduce grazing, cause human health impacts and have contributed to population crashes in the native fish and bird fauna (Tiwari et al. 2017). In particular, *P. juliflora* has major negative effects on soil and water system functioning and reduces biodiversity in several regions around the world (Shackleton et al. 2014) as it does in Keoladeo. *Paspalum distichum* is present in wetlands where it depletes oxygen and affects the survival of native floating plant species, fishes and waterfowl (Tiwari et al. 2017). *Lantana camara* competes with native species, is allelopathic and has impacts on native birds in other WHS in India (Aravind et al. 2010), and *P. hystrophis* displaces native species, reduces grazing and impacts animal and human health (Priyanka and Joshi, 2013; Adkins and Shabbir, 2014). *Eichhornia crassipes* dominates wetland areas, blocks artificial waterways and filling impoundments, thereby altering habitat for native bird species and altering ecosystem services (Villamagna and Murphy 2010; Keller et al. 2018). The invasive fish species *C. gariepinus* also presents a significant problem, predating on native fauna with negative effects in many introduced regions globally and in other parts of India (Vitule et al. 2006; Krishnakumar et al. 2011). *Cyprinus carpio* may also alter water quality, particularly though increasing turbidity (Weber and Brown, 2009). *Bos taurus* are abundant within the park and compete with the park’s herbivores for food and space (there is debate on their origin and “invasiveness”; Lewis, 2003). *Macaca mulatta* is also invasive and damages infrastructure and predates on eggs of several native bird species (M. Onial and K. Sivakumar, pers. com.). The invasive moth *P. diminutalis* is a major introduced pest and has altered the growth of *Nymphoides cristatum*, an important native aquatic plant.

Trends: Despite the lack of long-term monitoring the threats seem to be **increasing** based on expert opinions and the literature.

4. Management

Detailed information on management in the park is limited and there is some contention in the literature regarding the degree of success (Hockings et al. 2008). However, it is recognised as one of India's best managed parks (K. Sivakumar, pers. com.). There is no biosecurity in place and further accidental introductions from other land uses nearby are possible as is the natural spread from nearby areas.

There have been concerted efforts to manage *E. crassipes*, *P. juliflora* and other invasive plant species within the park with varying degrees of success. The removal of *E. crassipes* has been carried out relatively efficiently using labour from the Eco Development Committees (EDCs), which have been formed with 16 villages adjacent to the park (UNESCO, 2014). Despite successful initial attempts to eradicate *P. juliflora* in 2007-2008 through uprooting, fire and occasional flooding, the species has now become widespread and persists over the entire WHS. Park management has employed the local poverty alleviation programme, the Mahatma Gandhi National Rural Employment Guarantee Scheme, to carry out *P. juliflora* removal and monitor its spread within the park, with the villagers using *P. juliflora* for fuelwood. *Clarias gariepinus* is also being managed, with the support of local fishermen being enlisted to remove the fish. Despite such efforts, the numbers present in wetland areas appear to be increasing, with 7 304 fish removed in 2014-2015 compared to 40 117 removed in 2016 (https://timesofindia.indiatimes.com/city/jaipur/now-a-10-year-project-to-rid-keoladeo-of-african-catfish/articleshow/56138441.cms).

Assessment: Management is taking place, and knowledge of effectiveness is limited but suggests many challenges remain, therefore the site is categorised as facing **serious concern**.

Trends: Overall management responses are **increasing**.

5. Predictions on future threats/needs

Due to the lack of formal assessments in the region it is unknown what species might pose a future threat.

Future monitoring is needed, and a pathway analysis could be highly beneficial. Improved management implementation and novel solutions, in particular to address issues with *P. juliflora,* are needed.

Trends: Threats are likely to be **increasing** and the site is currently likely to be **incapable** of facing future challenges.

6. Knowledge status and gaps

Indicator	Status of knowledge	Confidence	Notes and recommendations
1. Introduction pathway Prominence	Low	Low	No detailed species by species assessments of pathways have been done, and we only present a broad overview here. More information is needed.
2. Species inventories	Low	Low	There is no full assessment and species inventory for the WHS, but there is evidence of at least 14 invasive species based on expert assessments and ex situ data collected from the literature. This is a start, but it is suspected that there may be more species present that have not yet been accounted for.
3. Impacts of IAS	Moderate	Moderate	There is some research taking place in the WHS especially for *P. juliflora* and *E. crassipes.* There is good understanding of the impact of many IAS present from research in other regions. More work could be done to improve novel insights for the site.
4. Management status	Low	Low	There are some publications and reports for the management of some species, but overall information is not available and attempts to make this public would be highly beneficial.
5. Future threats	Data deficient	Low	Unknown as there is limited information available.

7. Overall assessment

The current and potential threat of IAS in the Keoladeo WHS can be considered to be **High**. There are a number of high-profile IAS present at the site that are among the worst invasive species in the world and a major threat in many protected areas. It is unlikely that there is adequate capacity to deal with many of these threats.

Trends: Overall, the threat from IAS on this site is **increasing**.

References

Aravind NA, Rao D, Ganeshaiah KN, Shaanker RU, Poulsen JG (2010) Impact of the invasive plant, *Lantana camara*, on bird assemblages at Male Mahadeshwara Reserve Forest, South India. Trop Ecol 51: 325-338.

Adkins S, Shabbir A (2014) Biology, ecology and management of the invasive parthenium weed (*Parthenium hysterophorus* L.). Pest Manage Sci 70: 1023-1029.

Hockings M, James R, Stolton S, Dudley N, Mathur V, Makombo J, Courrau J, Parrish J (2008) Enhancing our Heritage Toolkit. Assessing Management Effectiveness of Natural World Heritage Sites. UNESCO: Paris, France.

Keller RP, Masoodi A, Shackleton RT (2018) The impact of invasive aquatic plants on ecosystem services and human well-being in Wular Lake, India. Reg Environ Change 18: 847-857.

Krishnakumar K, Ali A, Pereira B, Raghavan R (2011) Unregulated aquaculture and invasive alien species: a case study of the African Catfish *Clarias gariepinus* in Vembanad Lake (Ramsar Wetland), Kerala, India. J Threat Taxa, 3: 1737-1744.

Kumar S, Mathur M (2014) Impact of invasion by *Prosopis juliflora* on plant communities in arid grazing lands. Trop Ecol 55: 33-46.

Lewis M (2003) Cattle and Conservation at Bharatpur: A Case Study in Science and Advocacy. Conserv Soc 1: 1-21.

Priyanka N, Joshi PK (2013) A review of *Lantana camara* studies in India. Int J Sci Res Publ 3: 1-11.

McConnachie AJ, Strathie LW, Mersie W, Gebrehiwot L, Zewdie K, Abdurehim A, Abrha B, Araya T, Asaregew F, Assefa F, Gebre-Tsadik R (2011) Current and potential geographical distribution of the invasive plant *Parthenium hysterophorus* (Asteraceae) in eastern and southern Africa. Weed Research 51: 71-84.

Mukherjee A, Velankar AD, Kumara HN (2017) Invasive *Prosopis juliflora* replacing the native floral community over three decades: a case study of a World Heritage Site, Keoladeo National Park, India. Biodiv Conserv 26: 2839-2856.

Prusty BAK, Chandra R, Azeez PA, Sharma LL (2007) New Additions to the Ichthyofauna of Keoladeo National Park, a World Heritage Site in India. Zoos' Print J 22: 2848-2852.

Shackleton RT, Le Maitre DC, Pasiecznik NM, Richardson DM (2014) Prosopis: a global assessment of the biogeography, benefits, impacts and management of one of the world's worst woody invasive plant taxa. AoB PLANTS 6: plu027.

UNESCO (2014) Keoladeo National Park: Summary of the State of Conservation Report by the State Party. Available at: http://whc.unesco.org/document/128695.

Tiwari SK, Upadhyay RK (2017) Conservation of degraded wetland system of Keoladeo National Park, Bharatpur, India. Ecol Complex 32: 74-89.

Villamagna AM, Murphy BR (2010) Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. Freshw Biol 55: 282-298.

Vitule JR, Umbria SC, Aranha JMR (2006) Introduction of the African catfish *Clarias gariepinus* (BURCHELL, 1822) into Southern Brazil. Biol Invasions 8: .677.

Weber MJ, Brown ML (2009) Effects of common carp on aquatic ecosystems 80 years after "carp as a dominant": ecological insights for fisheries management. Rev Fish Sci 17: 524-537.

6. Serengeti National Park (Tanzania)

1. Pathways

The key pathways for IAS in the Serengeti National Park (SNP) have not been assessed at the species level but have been broadly assessed for the site. The most prominent pathways include: escape from confinement; particularly relating to horticulture, pets and farmed animals; as stowaways, particularly on vehicles, machinery/equipment, and tourists; through biological control; as well as unaided though natural dispersal (the most prominent pathway). A number of other pathways are not relevant, e.g. corridor pathway or escapees from fur farms, and any pathways relating to marine ecosystems. Biosecurity practices are not adequately implemented. With the population growing rapidly, and the country developing fast, there are likely to be an increasing number of pathways in the future.

CBD Pathway Category for introduction of IAS	Subcategory	Risk	Examples and/or notes	Trends
(1) Release in nature	Biological control	Very high	Numerous biological control agents have been released in the broader region and could spread into the park or be purposely introduced at some stage. *Dactylopius* species are already present on *Opuntia monacantha* and *O. ficus-indica* in areas adjacent to the WHS and may contribute to the control of these species if they were to establish there (Witt et al. 2018). There have been ongoing attempts to establish the biocontrol agent *Cecidochares connexa* on *Chromolaena odorata* and *Zygogramma bicolorata* on *Parthenium hysterophorus* in the region. A number of biocontrol agents have established on *L. camara* in the region and could be present in the WHS. All of these agents were appropriately evaluated and are host specific and safe.	Increasing
	Hunting	Very low	It is unlikely that any alien species will be intentionally introduced for this reason. They may be introduced into private lands in Tanzania and spread naturally into the park, but this is highly unlikely as there is a high abundance and diversity of native fauna for hunting. Hunting is also banned in Kenya so risks from cross border spread are low.	Stable
	Landscape/flora/fauna "improvements" in the wild	Low	It is unlikely any species will be introduced for this reason in the SNP. They may be introduced to private lands in surrounding areas, and then escape from confinement or cultivation and spread naturally into the park. Invasive plant species have been used for restoration in adjoining landscapes.	Stable
(2) Escape from confinement	Agriculture and horticulture (including biofuel feedstock)	High	Rapid increase in agricultural practices and general development in areas surrounding the park are increasing the risk of escapes. For example, species introduced for biofuels (e.g. *Jatropha* spp.) might escape planting and become invasive in the region (see Witt. 2010).	Increasing
	Aquaculture/mariculture	High	It is unlikely any fish species will be directly introduced into the SNP. However, several countries in the region are actively promoting aquaculture using alien fish species. With many of the rivers in the SNP emanating outside of the SNP, the risk of introduction is high through escape from rearing ponds and natural dispersal. There are reports of alien *Oreochromis* spp. in the area; these species are commonly used for aquaculture (Macdonald and Frame, 1988). These records need to be confirmed.	Increasing

	Pet/aquarium/terrarium species	Very high	There are many reported cases of feral dogs and cats in the SNP. Dogs are often also used for hunting. With increasing surrounding populations this pathway is likely to remain prominent (Shackleton et al. 2020).	Increasing
	Farmed animals (including animals left under limited control)	Very high	A number of farmed animals (cattle, goats, donkeys, etc.) are common in the bordering pastural lands and it is suspected that many of them stray into the park. It is, however, illegal for herders to allow livestock into the SNP.	Stable
	Forestry	High	Non-native species such as *Eucalyptus* spp., *Senna siamea*, *S. spectabilis*, and *Vachellia nilotica* ssp*. indica*, are often grown in woodlots in adjacent areas and have the potential to escape cultivation and spread into the SNP.	Increasing
	Horticulture	Very high	Many of the current IAS present have escaped from horticulture (e.g. *Lantana camara*). With increasing development in the surrounding areas, and numerous small roadside nurseries selling invasive species nearby, this pathway is highly prominent and relevant. Planting of alien species is also common in lodges and residential areas within parks in Africa (Foxcroft et al. 2008) and likely an issue in SNP, despite there being regulations preventing planting of alien species in all protected areas in Tanzania.	Increasing
	Other ornamental purposes	Low	Many alien species which are known to be invasive are used for hedges.	Stable
(3) Transport-**Contaminant**	Food contaminant (including of live food)	Moderate	With increasing tourism and movement of people in the region, there are likely to be increasing chances of species being introduced as food contaminants. There are, however, no good examples.	Increasing
	Parasites on animals (including species transported by host and vector)	Very high	Numerous domestic and feral animals enter the park. Feral dogs are carriers of rabies and canine distemper which is fatal to the endangered African hunting dogs (*Lycaon pictus*). Rinderpest, accidentally introduced through imported cattle from Asia in the late 1800s, had devastating impacts on native ungulates in SNP (Macdonald and Frame, 1988), although this disease was eradicated in 2011. Pastoralists in the region move their livestock over large areas, increasing the risk of parasite transmission.	Increasing
	Contaminant on plants (except parasites, species transported by host/vector)	Moderate	This has not been properly assessed or monitored but it its very likely this has occurred or will occur. However, most plants used in the SNP, and adjoining areas are acquired locally (or at least within Tanzania).	Unknown
	Parasites on plants (including species transported by host and vector)	Moderate	This has not been properly assessed or monitored but it its very likely this has occurred or will occur. There are a number of alien and invasive crop pests and diseases in the region, highlighting the relevance of this pathways (Pratt et al. 2017). It unknown whether any of these attack native species.	Increasing
	Seed contaminant	Moderate	Uncertified crop seed are traded to a great extent in the region, and are a potential pathway for introducing alien species such as *Striga hermonthica* (Shackleton et al. 2017).	Stable
	Timber trade	Low	This is not very common in the region. However, there are unconfirmed reports of the introduced Polyphagous Shot Hole Borer, *Euwallacea fornicatus*, in Uganda; this species could pose a serious threat to native tree species in the region should it spread more widely.	Stable

(4) Transport-**Stowaway**	Container/bulk	Moderate	With increasing development in the park, this pathway will likely become more serious over time – it is similar to stowaways on equipment which is known to be an issue.	Increasing
	Hitchhikers in or on a plane	High	Although there is no specific evidence for this pathway, with increasing tourism and private flights into the PA, this pathway is likely to, at some point, lead to additional introductions in the future. For example, *Parthenium hysterophorus* was detected at an airfield in the SNP and is likely to have been introduced through seeds in, or on, a plane.	Increasing
	Hitchhiker on vehicles/cargo*	Very high	It is very likely that numerous species being introduced and spread as hitchhikers on vehicles – this is especially likely with increasing tourism.	Increasing
	Machinery/ equipment	Very high	There is evidence that numerous species have been introduced and spread by machinery and equipment during the building of lodges and roads in the SNP (J.R. Mbwambo, pers. comm.).	Increasing
	People and their luggage/equipment (in particular tourism)	Very high	It is very likely and there is evidence of this from Kilimanjaro National Park nearby (Hemp, 2008).	Increasing
(5) **Corridor**	Interconnected waterways/basins/seas Tunnels and land bridges	N/A	There are no relevant structures.	N/A
(6) **Unaided by humans**	Natural dispersal across borders of IAS that have been introduced through pathways 1–5	Very high	There is considerable expansion of many invasive species in Tanzania. Detail roadside mapping as well as species distribution modelling highlight a large number of IAS that are likely to naturally spreads into the site in the future (Kija, et al. 2012; Riginos et al. 2015; Kilawe et al. 2017, Witt et al. 2017; Witt and Luke, 2017: Eckert et al. 2020). *Opuntia monacantha, O. stricta, Parthenium hysterophorus* and *Prosopis juliflora* are of high concern together with many other species.	Increasing

Trends: Although only a preliminary assessment is presented here, and further work is needed, it is suspected that the threat of most relevant pathways are **increasing**, as nearby regions and the park itself develops and as tourism increases.

2. Species inventory

There are 245 alien plant species in the broader Serengeti-Mara ecosystem, of which 62 are have established self-perpetuating populations away from human habitation (Witt et al. 2017). Of these, 23 are currently known to be invasive (Witt et al. 2017). This data is largely based on roadside surveys supported by more detailed observations of plants in tourist and other accommodation in the whole region, not just for SNP. This builds on previous surveys conducted by Macdonald and Frame (1988), Henderson (2002), and Foxcroft et al. (2006) which, indicate an increasing trend in the presence of alien and invasive alien species, mainly plants, in the SNP and the broader regional ecosystem (Witt et al. 2017; Shackleton et al. 2020). Only four animal taxa have been listed as invasive to date, including the mammals *Canis lupus familiaris, Felis catus, Rattus rattus* and the fish *Oreochromi*s spp. (although the latter is an old record which needs to be reconfirmed (Macdonald and Frame, 1988). In addition, it has been speculated that there are a number of micro-organisms, with known impacts from introduced rinderpest in the late 1800s (Macdonald and Frame, 1988) (although the disease was eradicated globally in 2011).

Trends: The number of invasive species is **increasing**.

3. Impacts
Species that are thought to cause current or potential negative impacts in the SNP include: *Lantana camara, Opuntia monacantha, O. stricta, Parthenium hysterophorus, Prosopis juliflora, Pistia stratiotes* and *Tithonia diversiflora* (Witt et al. 2017). Roadside surveys have revealed that most of these species are not yet very common in the SNP. However, they are widespread and abundant in adjoining areas and as such have the potential to invade and proliferate within the SNP (Wabuyele et al. 2014; Shackleton et al. 2017a, b; Witt et al. 2017; Shackleton et al. 2020). Evidence from studies in other regions of the world highlight that most of these species impact negatively on native biodiversity and ecosystems by altering natural processes, such as soil formation and fire regimes (O'Connor and van Wilgen, 2020; Qureshi et al. 2020). Some of these plants, including *L. camara* and *P. hysterophorus* also impact on animal health. Although the impacts of *O. monacantha* on animal health have not been studied, a congener, *O. stricta*, which is invasive elsewhere in the Serengeti-Mara ecosystem, is known to have negative impacts on livestock health. For example, the lodging of *O. stricta* glochids (tiny spines/thorns on the fruit) in the mouths, oesophagus, stomach lining and intestines causes secondary infections in livestock, and possibly also elephants (Shackleton et al. 2017c, while *L. camara* is toxic to livestock, and potentially other wildlife (Shackleton et al. 2017a). Some species also have negative impacts on ecosystem services, such as grazing potential for wildlife (e.g. *P. hysterophorus*) (Adkins and Shabbir, 2014) and invasive aquatic plants negatively impact water quality (e.g. *P. stratiotes*) (Villamagna and Murphy, 2010). *Parthenium hysterophorus* invasions are likely to have a dramatic impact on the annual wildebeest migration since this weed can reduce pasture carrying capacities by up to 90%. The invasive vertebrate species in the SNP are not considered to have very high impacts overall, although *F. catus* is known to hybridize with the African wild cat (*Felis lybica*) and *C. lupis familiaris* is a source of rabies and canine distemper in endangered African hunting dogs (*Lycaon pictus*) (Woodroffe et al. 2012; Le Roux et al. 2015).

Trends: The lack of monitoring and assessments makes it difficult to determine trends. Overall impacts from IAS are, however, suspected to be **increasing**.

4. Management
Management of IAS in the SNP has been very limited and *ad hoc* and this is of serious concern (Foxcroft et al. 2006; Witt et al. 2017). There have been some minor attempts to manage invasive and native weedy species in the broader Serengeti-Ngorongoro region but details are not well recorded (J.R. Mbwambo, pers. comm.).

There are no biosecurity operations in place and accidental introductions and natural spread from nearby areas is very likely (Witt and Luke, 2017; Witt et al. 2017). One preventive measure being implemented in the Serengeti-Ngorongoro area is that all lodges, in the broader conservation area, are mandated to remove alien species from their gardens and replace them with native species.

Since 2014, there has been an Earld Detection and Rapid Response EDRR campaign for *P. hysterophorus* in the SNP and Ngorongoro Conservation Area which seems to be more active in Ngorengoro. The plant is maunally uprooted and disposed of as soon as it is seen. *Parthenium hysterophorus* is also being managed in the Mara Triangle of the Maasai Mara National Reserve in Kenya, adjacent to the SNP, which forms part of the broader Serengeti-Mara ecosystem. Despite the management of *P. hysterophorus* in the Mara Triangle, this species continues to spread in other parts of the ecosystem. *Caesalpinia decapetala* is a potential threat and containment strategies have been conducted every few years since 2005, but mostly within the Ngorongoro Conservation Area.

Concerted efforts have been made to manage *Opuntia ficus-indica, O. monacantha, C. odorata* and other invasive plants in the Singita-Grumeti Concession adjacent to the SNP. Some attempts have been made to manage *O. monacantha* in the SNP itself, but we could find no information on the success of these efforts.

Agents for the biological control of *P. hysterophorus* have been introduced to Tanzania and will hopefully spread and establish in the SNP, therefore contributing to control (Witt et al. 2017). *Dactylopius opuntiae* has been released on *O. stricta* in Kenya, and may reach populations in the SNP through natural spread but could also be specifically introduced into the park in the future. Other *Dactylopius* species and/or biotypes are already present on *O. monacantha* and *O. ficus-indica* in areas adjacent to the SNP and may contribute to the control of these species. Biological control for cactus species has been successful elsewhere in Kenya but further monitoring is needed (Witt et al. 2020). There have been ongoing attempts to establish the biocontrol agent *Cecidochares connexa* on *C. odorata* in Tanzania but it is too soon to measure the success of this initiative. A number of biocontrol agents have established on *L. camara* in the region, but their effects still need to be assessed - although in other regions of the world biological control of this plant has had mixed results (Zalucki et al. 2007).

Assessment: Overall the management faces **serious concern**.

Trends: Management is **increasing** for the site, but more is needed.

5. Predictions on future threats/needs

A number of potential IAS recorded nearby, but not yet recorded in the Serengeti WHS, pose a major threat. These include *C. odorata* (which may already be present since the last surveys were undertaken), *Prosopis juliflora, Leucaena leucocephala, Tithonia diversifolia* and the ant *Pheidole megacephala,* which alters mutualisms and could cause negative impacts on keystone *Vachellia* species (Kija et al. 2012; Riginos et al. 2015; Kilawe et al. 2017; Witt et al. 2017; Witt and Luke, 2017; Eckert et al. 2020). Most of the information on invasive plants is based on roadside mapping and climatic suitability models and there is a good understanding of likely new threats.

Management is taking place, but long-term funding and monitoring is needed to assess effectiveness. Biological control should also be investigated further as a cost-effective approach to long-term management.

Trends: Threats are considered to be **increasing** and if these threats do emerge the site will be struggle to manage them.

6. Knowledge status and gaps

Indicator	Status of knowledge	Confidence	Notes and recommendations
1. Introduction pathway	Low	Low	No detailed assessments of pathways have been done for the SNP and this information is limited and based on expert opinion.
2. Species inventories	High	Moderate	There is good evidence of the introduced plant species present based on roadside surveys, expert assessments, local managers knowledge and ex situ data (Witt et al. 2017; Witt and Luke, 2017). For a national strategy on biological invasions for Tanzania data is further being collated. There was also past monitoring (Macdonald and Fume, 1988, Henderson, 2002 and Foxcroft et al. 2006), making it possible

			to determine trends, although many of these assessments need to be more comprehensive. They are also more region specific than site specific.
3. Impacts of IAS	Low	Low	There is no strong research on the impacts of IAS within the SNP, but there is evidence of impact for some species present in the WHS from studies conducted elsewhere.
4. Management status	Low	Low	There is limited information available, and management seems rather *ad hoc*. There is increasing knowledge on biological control in the region (Witt et al. 2020). Future information on management should be better collated and reported on.
5. Future threats	High	Hight	There is increasing information on the distribution of IAS in Tanzania including those that may pose a threat to the SNP. This has been backed up in many instances with roadside monitoring and species distribution models (Witt et al 2017; Witt and Luke 2017; Eckert et al. 2020).

7. Overall assessment

The threat of IAS to the Serengeti WHS can be consisted as **High** (the WHS was previously categorised as data deficient).

Trends: Due to increasing spread of high threat IAS, and very recent initiation of some full-time management it is likely the overall threat of IAS to this site is **increasing**. There is a lack of adequate data.

References

Adkins S, Shabbir A (2014) Biology, ecology and management of the invasive parthenium weed (*Parthenium hysterophorus* L.). Pest Manage Sci 70: 1023-1029.

Clark K, Lotter WD, Runyoro V (2010) Ngorongoro Conservation Area: Invasive Alien Plant Strategic Management Plan 2010. Ngorongoro Conservation Area Authority, Arusha, Tanzania.

Eckert S, Hamad A, Kilawe CS, Linders TEW, Ng WT, Mbaabu PR, Shiferaw H, Witt A, Schaffner U (2020) Niche change analysis as a tool to inform management of two invasive species in Eastern Africa. Ecosphere 11: e02987.

Foxcroft LC, Lotter WD, Runyoro VA, Mattay PMC (2006) A review of the importance of invasive alien plants in the Ngorongoro Conservation Area and the Serengeti National Park. Afr J Ecol 44: 404-406.

Foxcroft LC, Richardson DM, Wilson JR (2008) Ornamental plants as invasive aliens: problems and solutions in Kruger National Park, South Africa. Environ Manage 41: 32-51.

Hemp A (2008) Introduced plants on Kilimanjaro: tourism and its impact. Plant Ecol 197: 17-29.

Henderson L. (2002) Problem plants in Ngorongoro Conservation Area. Final Report Compiled 29 November 2002 for NCAA and FZS. L Henderson, Agricultural Research Council–Plant Protection Research Institute, stationed at National Botanical Institute, Private Bag X101, Pretoria 0001, South Africa.

Kilawe CJ, Mbwambo JR, Kajembe GC, Mwakalukwa EE, Amri AM, Mushi GV, Athumani AM, Eckert S. Eschen R (2017) Mrashia: Prosopis invading pastures and agricultural lands in Tanzania. The Woody Weeds Project. INSIGHTS Report.

Kija BJ, Mwaita M, Kittle A, Kija H (2012) Invasion of alien plants in Serengeti: A call for management action. TAWRI: Tanzania.

Le Roux JJ, Foxcroft LC, Herbst M, MacFadyen S (2015) Genetic analysis shows low levels of hybridization between African wildcats (*Felis silvestris lybica*) and domestic cats (*F. s. catus*) in South Africa. Ecol Evol 5: 288-299.

Macdonald IAW, Frame GW (1988) The invasion of introduced species into nature reserves in tropical savannas and dry woodlands. Biol Conserv 44: 67-93.

O'Connor TG, van Wilgen BW (2020) The impact of invasive alien plants on rangelands in South Africa. In: van Wilgen B, Measey J, Richardson DM, Wilson JR, Zengeya TA (Eds). Biological Invasions in South Africa. Springer, Cham. pp. 459-487.

Pratt CF, Constantine KL, Murphy ST (2017) Economic impacts of invasive alien species on African smallholder livelihoods. Glob Food Secur 14: 31-37.

Qureshi H, Anwar T, Habib N, Ali Q, Haider MZ, Yasmin S, Munazir M, Basit Z, Waseem, M (2020) Multiple comparisons of diversity indices invaded by *Lantana camara*. Braz J Biol (AHEAD): doi.org/10.1590/1519-6984.222147.

Riginos C, Karande MA, Rubenstein DI, Palmer TM (2015) Disruption of a protective ant-plant mutualism by an invasive ant increases elephant damage to savannas trees. Ecol 96: 654-661.

Shackleton RT, Witt ABR, Aool W, Pratt CF (2017a) Distribution of the invasive alien weed, *Lantana camara*, and its ecological and livelihood impacts in eastern Africa, Afr J Range Forage Sci 34: 1-11.

Shackleton RT, Witt ABR, Nunda W, Richardson DM (2017b) *Chromolaena odorata* (Siam weed) in eastern Africa: distribution and socio-ecological impacts. Biol Invasions 19: 1285-1298.

Shackleton RT, Witt AB, Piroris FM, van Wilgen BW (2017c) Distribution and socio-ecological impacts of the invasive alien cactus *Opuntia stricta* in eastern Africa. Biol Invasions 19: 2427-2441.

Shackleton RT, Foxcroft LC, Wood LE, Pyšek P, Richardson DM (2020) Assessing biological invasions in protected areas: revisiting targeted nature reserves 30 years after the 1980s SCOPE programme. Biol Conserv 243: 108424.

Villamagna AM, Murphy BR (2010) Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. Freshw Biol 55: 282-298.

Wabuyele E, Lusweti A, Bisikwa J, Kyenune G, Clark K, Lotter WD, McConnachie AJ, Wondi M (2014) A roadside survey of the invasive weed *Parthenium hysterophorus* (Asteraceae) in East Africa. J East Afr Nat Hist 103: 49-58.

Witt AB (2010) Biofuels and invasive species from an African perspective–a review. GCB Bioenergy *2*: 321-329.

Witt ABR, Kiambi S, Beale T, van Wilgen BW (2017) A preliminary assessment of the extent and potential impacts of alien plant invasion in the Serengeti-Mara ecosystem, East Africa. Koedoe 59: a1426.

Witt ABR, Luke Q (2017) Guide to the naturalised and invasive plants of eastern Africa. CABI, Wallingford UK.

Witt AB, Nunda W, Makale F, Reynolds K (2020) A preliminary analysis of the costs and benefits of the biological control agent *Dactylopius opuntiae* on *Opuntia stricta* in Laikipia County, Kenya. BioControl: doi.org/10.1007/s10526-020-10018-x.

Woodroffe R, Prager KC, Munson L, Conrad PA, Dubovi EJ, Mazet JA (2012) Contact with domestic dogs increases pathogen exposure in endangered African wild dogs (*Lycaon pictus*). PLoS ONE 7: pe30099.

Zalucki MP, Day MD, Playford J (2007) Will biological control of *Lantana camara* ever succeed? Patterns, processes & prospects. Biol Control 42: 251-261.

7. Vredefort Dome (South Africa)

1. Pathways

No detailed pathway analyses have been conducted for the Vredefort Dome. However, there are analyses of pathway prominence for South Africa as a whole (Faulkner et al. 2016) as well as an assessment for national parks in South Africa (Foxcroft et al. 2019) which provide good guiding information. Due to imperfect species lists and lack of capacity it is not feasible to do a full pathway analysis at this time. Based on expert opinion the most important five pathways are unaided spread of species introduced outside of the area, escape from confinement, particularly from horticulture but also forestry as a stowaway on vehicles, and as stowaway on people and their luggage/equipment. However, there is a lack of evidence in general.

CBD Pathway Category	Subcategory	Risk	Examples and/or notes	Trends
(1) Release in nature	Biological control, Fisheries in the wild	Low	Biological control initiatives are common in South Africa. Agents may not have been purposely introduced in the site, but they have spread naturally from other areas. More agents could easily be introduced to the site in the future. There is the potential for recreational angling species to have been purposely introduced into waterbodies in the site. Intentional release via other sub-pathways in the site are very unlikely.	Stable
(2) Escape from confinement	Forestry Horticulture Pet and aquaria species	High	A few species have likely escaped confinement from nearby areas and spread naturally into the site. This included horticultural plants from nearby towns (e.g. *Melia azedarach*), and trees from forestry (e.g. *Eucalyptus* species). Although there have been no recorded examples of this, it is possible that pets (cats and dogs) may escape and establish in the site. All the other sub-pathways are not likely to be relevant	Increasing
(3) Transport-**Contaminant**	All	Low	No direct examples are known for this pathway, and it is unlikely to be a prominent pathway.	Unknown
(4) Transport–**Stowaway**	Angling equipment, Vehicles, Machinery and equipment, People and their luggage	Moderate	There are no known and direct examples, but this is likely for *Campuloclinium macrocephalum,* which is a common stowaway on vehicles (Trethownan et al. 2011). Some might also may have been introduced as stowaways on angling equipment (Ellender and Weyl, 2014). Visitation rates are relatively low and so associated pathways may be limited by this. Some pathways relating to marine systems as well as aeroplanes are not relevant.	Unknown
(5) Corridor	Interconnected waterways and basins	Moderate	South Africa has interbasin water transfer schemes which are a known pathway - rivers in the site are connected to such transfer schemes (Ellender and Weyl, 2014).	Stable
(6) Unaided	Natural dispersal across borders of IAS that have been introduced through pathways 1–5	Very high	This is a key pathway for the introduced fish species at the site as well as most plants e.g. *Arundo donax, Cestrum laevigatum,* *Eichhornia crassipes* and many more. It is likely to be the most prominent pathway for potential future introductions, for example *Campuloclinium macrocephalum* and *Cylindropuntia imbricata* (Henderson and Wilson, 2017).	Increasing

2. Species inventory

Forty-four IAS have been recorded at the site, the majority of which (40) are plants, followed by four fish species. However, there are likely to be more species that have not been reported. This list was compiled though *ex situ* data (South African Plant Invader Atlas), expert option, and species reported by the Working for Water management programme and there maybe be more species if local in-depth assessments were done. *Arundo donax* and *Eucalyptus* spp. are very common along the water bodies of the WHS while other species are less prominent and more sporadic. Several invasive fish species are present and widespread in the waterbodies that flow though the WHS. They include *Ctenopharyngodon idella*, *Cyprinus carpio*, *Gambusia affinis* and *Lepomis macrochirus*. These invasive fish species affect native aquatic species and water quality. Although not confirmed it is also likely that *Micropterus salmoides* and *Micropterus dolomieu* and the extra-liminal fish species *Oreochromis mossambicus* are also present.

Trends: Overall trends cannot be assessed due to data deficiency and are therefore **unknown**.

3. Impacts

No formal studies of the impact of IAS on the WHS have been conducted. Based on expert opinion, IAS considered to have substantial impact include *Arundo donax*, *Cestrum laevigatum***,** *Eichhornia crassipes*, a few *Eucalyptus* spp., *Gleditsia triacanthos*, *Melia azedarach, Myriophyllum aquaticum*, a few *Opuntia* spp. and *Tamarix ramosissima* (Henderson and Wilson, 2017). These species all have negative impacts on biodiversity, and some also disrupt ecosystem structure and processes, for example by altering hydrological regimes, reducing grazing potential for wild animals and altering soil chemistry (Versfeld and van Wilgen, 1986; Villamagna and Murphy, 2010). Floating aquatic weeds and *A. donax* impact the aesthetic appeal of water bodies and reduce recreation value for visitors around water bodies (Keller et al. 2018). The predatory invasive fish species listed negatively affect native species richness (Yonekura et al. 2004), and *Cyprinus carpio* and *Ctenopharyngodon idella* can impact water quality through increasing turbidity causing habitat degradation and can cause trophic cascades (Kloskowski et al. 2011). It is not known if any native species are under threat of extinction due to these invasive plants. It must be noted that this site was primarily inscribed for its geological characteristics which invasive species are unlikely to affect greatly, however, they could affect recreation, aesthetic and biodiversity values on the site which are also important to preserve.

Trends: The prominence and change in overall threat is **unknown** due to data deficiency, but is likely to be stable or increasing.

4. Management

Currently, no biosecurity is underway, and IAS could be introduced accidently in the future. South Africa has the world-famous Working for Water program (WfW), which is mandated to manage IAS to restore ecosystems and provide employment to improve rural development (van Wilgen and Wannenburgh, 2016). WfW is active in the Vredefort Dome where it is working on several of the species mentioned above, as well as the alien invasive *Populus* spp. and the weedy native plants *Asparagus laricinus* and *Seriphium plumosum,* with the aim of containment and impact reduction. The programme employs 10-20 people to do this work and has an annual budget of around R 100

000 (± US$ 8 000). Broadly speaking, on a national level, this programme does face some social, ecological and economic barriers which hinders success (Shackleton et al. 2016). The regional managers highlight that the IAS they are targeting are still present but in decline as a result of long-term steady commitment to management. Of concern are invasive fish, which are hard to manage once widely established in large rivers and known to negatively affect native biodiversity (Woodford et al. 2020). A number of biological control agents are present on some of these species in South Africa. Biological control of *E. crassipes*, *M. aquaticum* and *Opuntia ficus-indica* has been successful in most areas of the country and is likely to also be successful in the WHS (Hill and Coetzee, 2017; Zachariades et al. 2017). Agents have recently been released for the control of *C. macrocephalum* but more monitoring is needed to determine the success of the program (Ramanand et al. 2016). South Africa has a long history of successful biological control initiatives and it is likely this will continue and help to manage more widespread and high impact IAS such as invasive grass species of which one candidate could be *A. donax* (Sutton et al. 2019).

Assessment: Due to good biological control and long-term commitment form the WfW program, management can be considered as **effective**. Management of invasive fish is still of concern.

Trends: Management is currently **stable**.

5. Predictions on future threats/needs

Major emerging and potentially IAS include *Campuloclinium macrocephalum* and *Cylindropuntia imbricata* (Henderson, 2007; Henderson and Wilson, 2017). This is based on localised monitoring of species through the South African Plant Invaders Atlas (SAPIA) program.

In terms of management, an in-depth survey and species list would be useful, as well as monitoring of management success. Early detection and rapid response should be initiated for new arrivals.

Trends: Threats could be considered as **stable** and future management is likely to be **capable** of dealing with them.

6. Knowledge status and gaps

Indicator	Status of knowledge	Confidence	Notes and recommendations
1. Introduction pathway	Low	Low	No detailed species by species assessments of pathways have been done for the WHS and this is something that would be useful in the future. There is good understanding for the whole country, but this is a bit course (Faulkner et al. 2016), there are also information available form a detailed pathway assessment for National Parks in South Africa which gives good inference for this WHS.
2. Species inventories	Low	Low	There is no full assessment and an exact species list, but there is evidence of at least 44 species based on expert assessments, local managers knowledge and ex situ data
3. Impacts of IAS	Low	Low	No research on impacts of IAS in the WHS, but there is evidence of impact for some species present form studies conducted elsewhere in South Africa and the world.
4. Management status	Moderate	Moderate	There is good understanding of the effectiveness of biological control. Management is being undertaken by the national scale and long-term Woking for Water Program – but exact evidence of success is lacking. The lead WfW manager for the site has indicated that all targeted species are stable or

			decreasing in extent but monitoring of changes in exact distribution would be useful.
5. Future threats	Low	Low	A recent paper assessing trends over time (Wilson and Henderson, 2017), based on national scale monitoring of IAS (SAPIA), indicates numerous changes and species that occur near to the WHS that might become problems in the future.

7. Overall assessment

The current and potential threat of IAS to the Vredefort Dome WHS can be considered as **moderate** (no threat level was listed previously). There are a few high impact species present, but there has been long-term management and the threat seems to remain stable.

Trends: Inadequate knowledge precludes discernment of clear trends, but threats appear to be **stable**, as good management initiatives are in place. More detailed monitoring is needed.

References

Ellender BR, Weyl OL (2014) A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. Aquat Invasions 9: 117-132.

Faulkner KT, Robertson MP, Roget M, Wilson JRU (2016) Understanding and managing the introduction pathways of alien taxa: South Africa as a case study. Biol Invasions 18: 73-87.

Foxcroft LC, Spear D, van Wilgen NJ, McGeoch MA (2019) Assessing the association between pathways of alien plant invaders and their impacts in protected areas. NeoBiota 43: 1-25.

Henderson L, (2007) Invasive, naturalized and casual alien plants in southern Africa: a summary based on the Southern African Plant Invaders Atlas (SAPIA). Bothalia 37: 215-248.

Henderson L, Wilson JRU (2017) Changes in the composition and distribution of alien plants in South Africa: An update from the Southern African Plant Invaders Atlas. Bothalia 47: 1-26.

Hill MP, Coetzee J (2017) The biological control of aquatic weeds in South Africa: Current status and future challenges. Bothalia 47: 1-12.

Keller RP, Masoodi A, Shackleton RT (2018) The impact of invasive aquatic plants on ecosystem services and human well-being in Wular Lake, India. Reg Environ Change18: 847-857.

Kloskowski J (2011) Impact of common carp *Cyprinus carpio* on aquatic communities: direct trophic effects versus habitat deterioration. Fund App Limnol 178: 245-255.

Ramanand H, Olckers T, McConnachie A (2016) Response of the invasive pompom weed, *Campuloclinium macrocephalum* (Asteraceae), to feeding by the foliage-deforming thrips *Liothrips tractabilis* (Phlaeothripidae) under outdoor conditions in South Africa. Biocontrol Sci Tech 26: 1643-1651.

Shackleton RT, Le Maitre DC, van Wilgen BW, Richardson DM (2016) Identifying barriers to effective management of widespread invasive alien trees: Prosopis species (mesquite) in South Africa as a case study. Global Environ Change 38: 183-194.

Sutton GF, Canavan K, Day MD, den Breeyen A, Goolsby JA, Cristofaro M, McConnachie, A, Paterson ID (2019) Grasses as suitable targets for classical weed biological control. BioControl: 64: 605-622.

Trethowan PD, Robertson MP, McConnachie AJ (2011) Ecological niche modelling of an invasive alien plant and its potential biological control agents. S Afr J Bot 77: 137-146.

van Wilgen BW, Wannenburgh A (2016) Co-facilitating invasive species control, water conservation and poverty relief: achievements and challenges in South Africa's Working for Water programme. Curr Opin Env Sust 19: 7-17.

Versfeld DB, van Wilgen BW (1986) Impact of woody aliens on ecosystem properties. In: The ecology and management of biological invasions in Southern Africa. Proceedings of the National Synthesis Symposium on the ecology of biological invasions. Oxford University Press. pp. 239-246.

Villamagna AM, Murphy BR (2010) Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. Freshw Biol 55: 282-298.

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OL (2017) Optimising invasive fish management in the context of invasive species legislation in South Africa. Bothalia 47: 1-9.

Yonekura R, Kita M, Yuma M (2004) Species diversity in native fish community in Japan: comparison between non-invaded and invaded ponds by exotic fish. Ichthyol Res 51: 176-179.

Zachariades C, Paterson ID, Strathie LW, Hill MP, van Wilgen BW (2017) Assessing the status of biological control as a management tool for suppression of invasive alien plants in South Africa. Bothalia 47: a2142.

Supplementary file 3:

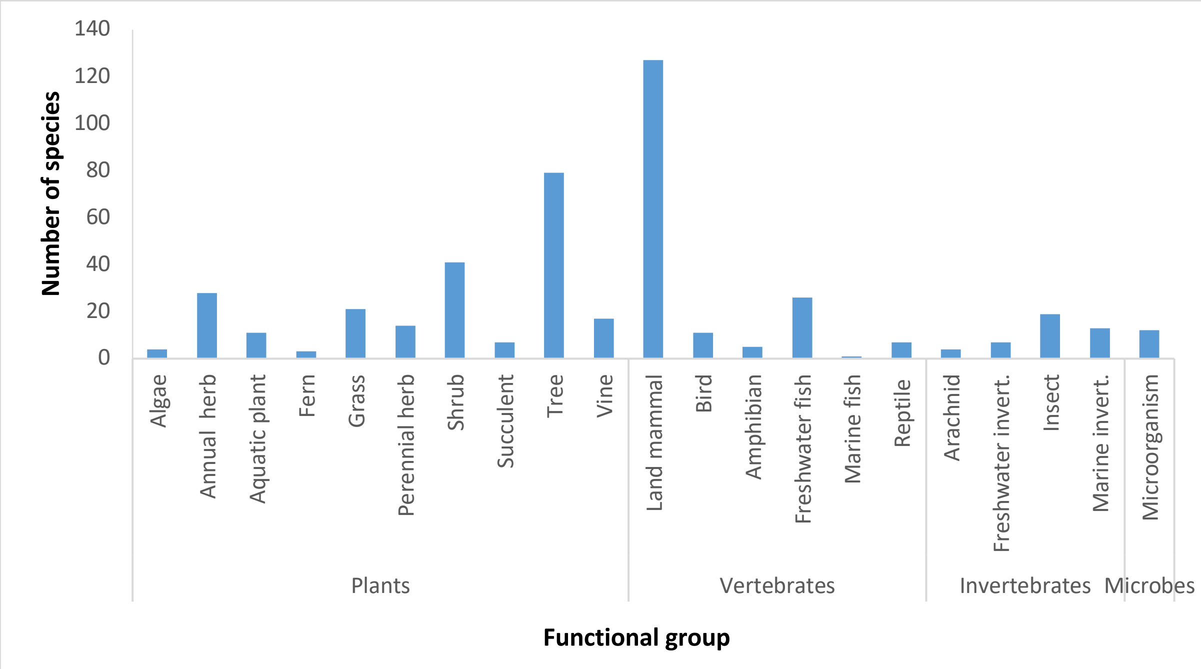

Fig 1 The number of invasive alien species recorded in the natural and mixed World Heritage sites (WHS) within different functional groups

Table 1 The most common invasive alien taxa reported in the 241 natural and mixed World Heritage Sites (WHS) globally on UNESCO and IUCN websites and in documents available on those websites. The table shows species that were found in three or more WHS

Rank	Taxon	Common name	No. of WHS	Functional group
1	*Rattus* spp.	Rat	18	Land mammal
2	*Felis catus*	Cat	17	Land mammal
3	*Capra hircus*	Goat	12	Land mammal
4	*Sus scrofa*	Feral pig	10	Land mammal
	Lantana camara	Lantana	10	Shrub
5	*Mus musculus*	House mouse	9	Land mammal
	Oryctolagus cuniculus	European rabbit	9	Land mammal
6	*Oncorhynchus mykiss*	Rainbow trout	7	Fish
7	*Canis lupus familiaris*	Dog	6	Land mammal
	Chromolaena odorata	Siam weed	6	Shrub
	Eichhornia crassipes	Water hyacinth	6	Aquatic plant
8	*Acacia* spp.	Wattles	5	Tree
	Casuarina equisetifolia	Beefwood	5	Tree
	Mimosa spp.	Mimosa	5	Shrub/perennial herb
	Eucalyptus spp.	Gum	5	Tree
9	*Argemone mexicana*	Mexican poppy	4	Annual herb
	Bos spp.	Cattle	4	Land mammal
	Cytisus scoparius	Scotch broom	4	Shrub
	Mikania micrantha	Mile-a-minute	4	Vine
	Phytophthora cinnamomi	Root rot	4	Microorganism
	Oreochromis spp.	Tilapia	4	Fish
	Vulpes vulpes	Red fox	4	Land mammal
	Datura stramonium	Jimsonweed	4	Annual herb
	Prosopis spp.	Mesquite	4	Tree
10	*Dreissena polymorpha*	Zebra mussel	3	Marine invertebrate
	Equus caballus	Horse	3	Land mammal
	Leucaena leucocephala	Leucaena	3	Tree
	Linepithema humile	Argentine ant	3	Insect
	Nyctereutes procyonoides	Racoon dog	3	Land mammal
	Opuntia stricta	Erect prickly pear	3	Succulent
	Parthenium hysterophorus	Parthenium	3	Annual herb
	Pinus nigra	Austrian pine	3	Tree
	Psidium guajava	Guava	3	Tree
	Ulex europaeus	Gorse	3	Shrub